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[1] Previous studies show there are significant thermospheric responses to the two great solar flares on October 28, 2003 (X17.2) and November 4, 2003 (X28). In the present study, we further explored the thermospheric response to all X-class solar flares during 2001–2006. The observed results show that X5 and stronger solar flares can induce an average enhancement of 10–13% in thermospheric density in latitude 50°S–50°N within ~4 h after the flare onset. Many important lines and continua in solar EUV region are optically thick, thus EUV enhancements are smaller for flares located near the solar limb due to absorption by the solar atmosphere. Limb flares induce smaller thermospheric responses, due to the limb effect of solar EUV. The thermospheric density enhancement is much more correlated with integrated EUV flux than with peak EUV flux, with a high correlation coefficient of 0.91, which suggests that thermospheric response is strongly dependent on the total integrated energy into the thermosphere.


1. Introduction

[2] Solar extreme ultraviolet (EUV) and X-ray photons are the primary energy source of the ionosphere and thermosphere of the Earth. A solar flare is a sudden eruptive solar phenomenon, associated with significant enhancements in EUV and X-ray radiations, with larger enhancements in X-rays and relatively smaller enhancements in long wavelength EUV. These emissions cause sudden and intense increases in ionization at various levels in the Earth’s ionosphere [e.g., Afraymovich, 2000; Leonovich et al., 2002; Liu et al., 2004, 2006; Tsurutani et al., 2005; Wan et al., 2005; Zhang et al., 2002; Zhang and Xiao, 2005; Le et al., 2007].

[3] Most previous studies related to solar flares have so far focused on the ionospheric responses [Afraymovich, 2000; Zhang et al., 2002; Le et al., 2007; Liu et al., 2011]. Only recently have studies been performed to quantify the thermospheric response to flares using observations and modeling [e.g., Sutton et al., 2006; Liu et al., 2007; Pawlowski and Ridley, 2008]. These studies show that in addition to the great disturbances in the ionosphere, solar flares can also induce significant responses in the thermosphere. Sutton et al. [2006] reported the first measurements of the thermosphere density response to two great flare events on 28 October 2003 and 04 November 2003. They found the thermosphere density increases associated with the flares are about 50–60% and 35–45%, respectively, at low to midlatitudes. Liu et al. [2007] examined the thermospheric and ionospheric responses to the solar flare on 28 October 2003 by using measurements from the CHAMP satellite. They found the contrasted behavior between the thermosphere and ionosphere: the neutral density was enhanced by 20% almost homogeneously at all latitudes below 50°S–50°N; the plasma disturbance exhibited a distinctive latitudinal structure, with largest density enhancements of 68% at the dip equator, moderate increase of 20% at midlatitudes. Pawlowski and Ridley [2008] simulated the thermospheric responses to the solar flare on 28 October 2003 using the Global Ionosphere-Thermosphere Model. The results show that the thermospheric density at 400 km can increase by as much as 14.6% in about 2 h and takes 12 h to return back to a nominal state. The flare irradiance spectral model (FISM) is an empirical model that estimates the solar irradiance at wavelengths from 0.1 to 190 nm at 1 nm resolution. It has a high temporal resolution of 60 s to model variations due to solar flares (for details please see Chamberlin et al. [2007, 2008]). Using the solar spectra data from the FISM model as solar input to the National Center for Atmospheric Research (NCAR) thermosphere-ionosphere-mesosphere electrodynamics general circulation model (TIME-GCM), Qian et al. [2010] investigated the ionosphere/thermosphere response to an X17 solar flare. The results also show the significant thermospheric disturbances including about a maximum increase of 85 K in neutral temperature and 20% in neutral density at height of 400 km.

[4] The studies mentioned above mainly focus on cases study for the thermospheric responses to the great solar flares on 28 October 2003 and 04 November 2003. It is not clear how the thermosphere responds to other weaker flares.
In this study, we analyze the neutral density variation for all X-class solar flares during 2001–2006 based on the density data derived from accelerometers on the Challenging Minisatellite Payload (CHAMP) and Gravity Recovery and Climate Experiment (GRACE) satellites.

2. Data Analysis

[5] In present study, we use total neutral density derived measurements of neutral density obtained from the accelerometers aboard CHAMP and GRACE satellites. With a near-polar inclination, the satellite provides near-global coverage at an approximate altitude of 410 km within two local time sectors at most latitudes. It takes about two months to sweep through 12 h of local time. The satellite GRACE is similar to the satellite CHAMP but has a higher orbit. Acceleration, attitude, and orbit ephemeris data files were used in the calculations. The derivation of thermosphere densities from these data is complex, and involves consideration of such effects as radiation pressure, satellite shape and orientation, thruster firings, etc. For detailed documentation about the calculation of density data from satellite accelerometers, please see Sutton et al. [2005]. All density data has been averaged into 3-degree latitudinal bins to reduce any random errors. In addition, neutral density has also been normalized to 2 heights (400 km and 410 km) using the NRL-MSISE-00 empirical density model.

[6] In order to examine the neutral density responses to solar flares, the changes between the density during a solar flare and during quiet conditions need to be calculated. As mentioned above, all density data have been averaged into 3° latitudinal bins from −90° to 90° with an interval of 3°. For each latitude bin, the mean of three orbits before the flare onset is calculated as the reference value. Thus we can get the reference value at each latitude bin. The period of orbit is about 94 min. There are about 15.4 orbits in a day. In a short time of no more than one day, the satellite covers the different longitude region in different orbit but the local time of each orbit is almost the same. The neutral density has a significant local time variation but has small longitudinal variation. On the basis of neutral density data from CHAMP, Liu et al. [2009] reported the neutral density exhibits a pronounced wave-4 longitudinal pattern in low latitudes, but its peak-trough amplitude is 2 ± 0.2% of the background neutral density, which is much smaller than the enhancement induced by solar flares as mentioned above. Thus, the longitudinal difference is ignored and we can obtain the solar flare effect on the neutral density by comparing the observed data to the reference data (the mean of the previous 3 orbits).

3. Results and Discussion

[7] To investigate the neutral density responses to solar flares, the responses of first three orbits (corresponding to the time within about 4 h) after solar flare onset are calculated and their mean is taken as the response for the solar flare. For each solar flare, the percentage variations (∆Nn) in different latitude bins are calculated. All solar flares are separated into three species: X1−2, X2−5, and X5−30. The neutral density can be significantly affected by geomagnetic storm [e.g., Forbes et al., 2005; Liu and Lühr, 2005; Sutton et al., 2005; Bruinsma et al., 2006]. In addition, on the basis of the analysis of thermosphere densities from the CHAMP and GRACE satellites, Lei et al. [2011] also reported the rapid recovery of 6–8 h. Thus, to reduce the geomagnetic activity effects, a solar flare event is excluded if the Kp index exceeds 4 within 12 h before the solar flare onset or 4 h after the solar flare onset (this 4 h correspond to the time of first three orbits), or the relative change in Kp index exceed 3 in the corresponding period. Although there are some geomagnetic disturbances, the great solar flare events on 28 October 2003 and 4 November 2003 are included for investigation because several studies [e.g., Sutton et al., 2006; Liu et al., 2007] have reported the significant thermosphere responses to the two solar flares. According this condition, for the CHAMP satellite, the number of solar flares having measurements is 20, 11, and 10 for the three species, respectively. For the GRACE satellite, the number of solar flares having measurements is 15, 5, and 8, respectively. In addition, the solar flare on 20 January 2005 is also excluded due to the early observation time (LT = 6.5) which is around the sunrise time.

[8] The range of background fluctuations is an important reference to scale the flare effect on the neutral density. For the measurements of CHAMP, there are about 15 orbits each day. We calculated the percentage change of standard deviation comparing to the median for each magnetic quiet day (Kp < 4) during 2001–2006. Then the mean percentage change at each latitude bin can be calculated. The statistical results show the mean range of fluctuation for middle-low latitudes (within ±50 degree) is about 6.5% of the background median.

[9] The corresponding results are plotted in Figure 1 (left plots for CHAMP and right plots for GRACE). The mean response for each species is also calculated and plotted in the panel. As illustrated in Figure 1, the measurements from CHAMP (GRACE) show that the mean response for latitudes within ±50° is about 0.75% (1.4%), 3.01% (4.86%), and 10.86% (13.63%) for solar flares of X1−2, X2−5, and X5−30, respectively. This mean response at a latitudinal bin refers to the average of first three orbits after solar flare onset. As mentioned above, the range of background fluctuation is about 6.5%. Therefore, the results (as shown in Figure 1) suggest that there is almost not any solar flare effect on the neutral density for X1−2, very slight solar flare effect for X2−5, and much stronger solar flare effect for X5−30. That is, the neutral density response increases with increasing flare strength and there is significant response for flares larger than X5.

[10] As mentioned above, the observed results show a significant neutral density response to solar flares with class larger than X5. Thus to clearly see the neutral density response for these flares, we illustrate the raw observations for the 15 X5–30 flares since 2001 in Figure 2. The Kp index is also marked in the figure. As shown in Figure 2, there are significant neutral density enhancements just shortly after the flare onset for solar flares on 4/2/2001, 4/6/2001, 10/28/2003, 11/2/2003, and 11/4/2003. These enhancements occurred mainly at low and middle latitudes and there is much less variation at high latitudes. Furthermore, the variations of Kp index show that there is no obvious geomagnetic activity during these solar flare events. On the basis of model simulations, Qian et al. [2011] also showed that the latitude dependence of thermosphere responses to solar flares
well correlated with the solar zenith angle effect: the large thermosphere responses occurring at low and middle latitudes due to the small solar zenith angle. However, the neutral gas disturbances related with the geomagnetic activity often started at high latitudes and then propagated to lower latitudes [Bruinsma et al., 2006; Lei et al., 2011]. Thus, the significant enhancements mainly occurring at low and middle latitudes strongly suggest that these responses should be caused by an increase in solar radiation flux.

[11] Figure 2 also shows that there are some enhancements in neutral density during solar flares on 8/25/2001, 10/29/2003, 9/9/2005, and 12/6/2006. However, the enhancements during these events not only occurred in low and middle latitudes, but also occurred in high latitudes and pole region. Furthermore, the enhancements first appeared in the high latitudes and then propagated to the lower latitudes. In addition, the enhancements do not just occur after the flare onset; in contrast, some of them have happened before the solar flare onset. As illustrated in Figure 2, the Kp index increased significantly during the four solar flare event. Thus, judging from the results as mentioned above, one can come to a conclusion that the enhancements in neutral density during solar flares on 8/25/2001, 10/29/2003, 9/9/2005, and 12/6/2006, are mainly contributed to by geomagnetic activity increases, not induced by solar flare effect.

**Figure 1.** The mean percentage changes in neutral density at three orbits after the solar onset for each flare (dotted line). Solar flares are separated into three species: X1–X2, X2–X5, and X5–X30. For each species, the mean response for the corresponding solar flares is also shown (solid line) in each panel. (left) CHAMP measurements and (right) GRACE measurements.
In addition, as illustrated in Figure 2, there is no obvious neutral density response to solar flares on 12/13/2001, 10/23/2003, 1/20/2005, 9/7/2005, 9/8/2005, and 12/5/2006. With the exception of the solar flare on 12/13/2001, these solar flare events have a common feature: limb flare with central meridian distance (CMD) larger than 60 degree. It is known that the ionospheric responses to solar flares have a significant dependence on solar location (CMD value) [Zhang et al., 2002; Tsurutani et al., 2005; Mahajan et al., 2010]. Then a question arises as to whether there is the same solar location effect for the thermospheric response and what factors can affect or control the thermospheric response. Qian et al. [2010] investigated the flare location effect on ionosphere/thermosphere responses by the TIME-GCM model with two different solar irradiance inputs derived from FISM model: one is for center flare and the other is for limb flare. The results show that flare-driven changes in the F region ionosphere, total electron content, and neutral density in the upper thermosphere, are 2–3 times stronger for a disk-center flare than for a limb flare, due to larger EUV enhancements for a disk-center flare.

As is known, the most important source of external forcing to the thermosphere is solar extreme ultraviolet (EUV) and soft X-ray (XUV) irradiation which results in the dissociation and ionization of background atmosphere from roughly 90 km to 200 km. During solar flares, the incident solar radiations carry much more energy than the requirement of dissociation and ionization of the gas. The leftover energy can further heat the neutral gas. The much enhanced radiations produce much more ionizations and high energy photoelectron, which also further transfer the energy to the neutrals by collisions. The heating causes the expansion of
the thermosphere, which results in the enhancements of neutral density as observed by the CHAMP and GRACE. During a solar flare, the soft X-ray and parts of the extreme ultraviolet (EUV) irradiance can increase by as much as a factor of 50 in minutes [Woods et al., 2004].

As mentioned above, CMD value might also be one of the important factors for the response of upper atmosphere to a solar flare. Thus, to further analyze the relationship between neutral density responses and X-ray and EUV flux, as well as the flare location effect, we plotted percentage enhancement in neutral density measured by CHAMP satellite versus peak X-ray flux and peak X-ray flux*Cos(CMD), time-integrated X-ray during 10 X-class solar flares, peak EUV and time-integrated EUV during 7 X-class solar flares in Figure 3. The data of X-ray flux (0.1–0.8 nm) from GOES satellite and the data of EUV (26–34 nm) from the SOHO satellite are used in this study. The 10 solar flares are selected from 15 X-class flares; the four flares on 8/25/2001, 10/29/2003, 9/9/2005, and 12/6/2006 are excluded due to the significant geomagnetic activity and CHAMP satellite has no measurement during the flare on 1/20/2005. In addition, only 7 flares are left to be used in the analysis for the relation between EUV flux and $\Delta N_n$ due to no EUV measurement during the three solar flares on 9/7/2005, 9/8/2005, and 12/5/2006. For each solar flare, the value of $\Delta N_n$ averaged over $\pm 50^\circ$ latitude represents the neutral density response to the solar flare.

As shown in Figure 3a, the correlation between the $\Delta N_n$ and peak X-ray flux is very poor; its correlation coefficient is only 0.30. To consider flare location effect, we calculated the values of peak X-ray*Cos(CMD) and illustrated the dependence of $\Delta N_n$ on peak X-ray*Cos(CMD). Figure 3b shows a much higher correlation coefficient (0.85) between them. The large difference between the results in Figures 3a and 3b suggests that the thermosphere responds differently depending on flare location on the disk. It is known that X-ray flux intensity is independent of solar origin location [e.g., Mosher, 1979; Samain, 1979]. Their results indicated that the EUV and UV radiation intensity decreases when a radiation source moves from the central solar meridian to the limb, whereas the intensity of soft X rays remains almost unchanged. Thus, we use peak X-ray*Cos(CMD) to reflect the flare location effect on the EUV flux. That is, for the same class solar flare (the same value of peak X-ray flux), the larger value of CMD means the smaller value of peak X-ray*Cos(CMD), which represents the smaller EUV flux. The higher correlation between neutral density response with peak X-ray*Cos(CMD) than with peak X-ray flux indirectly reflects the flare location effect on the EUV flux, as neutral density response mainly comes from the enhancements in EUV flux.

Mahajan et al. [2010] and Zhang et al. [2011] also used the same method to investigate the flare location effect on the ionospheric response...
to solar flares, which also represents the location effect on the EUV flux.

[16] The dependence of $\Delta N_n$ on peak EUV flux is illustrated in Figure 3d, the results show a relative low correlation coefficient (0.65) between the $\Delta N_n$ and peak EUV flux, but it is still much better than that between the $\Delta N_n$ and peak X-ray flux. Furthermore, Figure 3e shows a much higher correlation coefficient (0.91) between the $\Delta N_n$ and time-integrated EUV flux. The time-integrated EUV flux is integrated between the onset and end of a solar flare. Because the large mass and high heat capacity in the thermosphere, the neutral gas response to a solar flare would be sluggish with regard to transient enhancement in EUV and X-ray flux, which typically lasts less than one hour. In other words, it needs longer time for neutral gas to react to the increase in EUV and soft X-ray flux, and the neutral gas response also can last a longer time. Such a character causes that neutral density would increase gradually until to the end of a solar flare. Thus neutral gas responses are related to the total solar EUV coming into the thermosphere. For the comparison, we also show the relation of $\Delta N_n$ with the time-integrated X-ray flux in Figure 3e. The correlation coefficient between them is only 0.27, which again suggest that neutral density response mainly comes from the enhancements in EUV flux not that in X-ray flux.

[17] Comparing to the slow responses in the thermosphere, the ionosphere responds much faster due to the small time constant of electron and ions. The time and amplitude of peak response is determined by peak solar irradiance [e.g., Afraimovich, 2000; Zhang et al., 2002; Le et al., 2007]. In addition, the simulations based on Global Ionosphere-Thermosphere Model (GITM) and synthetic solar irradiance data during a solar flare [Pawlowski and Ridley, 2011] also suggest that the neutral density response at 400 km altitude is linearly dependent on the total integrated energy throughout the duration of a solar flare above the background level being deposited into the atmosphere. Therefore, the correlation of $\Delta N_n$ and time-integrated EUV is better than that of $\Delta N_n$ and peak EUV, as shown in Figures 3d–3e.

[18] For better analysis of the neutral density response to the 15 solar flares, we list the detailed information for each solar flare in Table 1, including peak X-ray flux, CMD value, modified peak X-ray flux, peak EUV flux, time-integrated EUV flux, $\Delta N_n$, and variation of Kp index. As shown in Table 1, although the X6.2 flare on 12/13/2001 is a central flare with CMD = 9°, it has a much smaller time-integrated EUV flux of $3.35 \times 10^{13}$ photons/cm² compared to other flares, which results in a small neutral density response of $\Delta N_n = 6.12\%$. Table 1 also shows solar flares on 10/23/2003 (X5.4), 9/7/2005 (X17), 9/8/2005 (X5.4), and 12/5/2006 (X9) have small neutral density responses with $\Delta N_n < 10\%$, which is due to the large values of CMD. Even the great X28 solar flare on 11/4/2003 only has a small value of $\Delta N_n = 9.6\%$. Actually, because the neutral density response is highly controlled by EUV flux variation, one can come to a conclusion that the dependence of neutral density response on solar flare location is mainly due to the solar flare location effect on solar EUV enhancements. Le et al. [2011] statistically analyzed the relationship between enhancements in X-ray flux and in EUV flux for solar flares during 1999–2006. The results show a significant flare location effect on EUV enhancements for X-class solar flares. One of the reasons for the flare location effect on solar EUV variation is that solar EUV is produced lower in the solar atmosphere than soft X-ray [Donnelly, 1976]. The more important factor is that many bright chromospheric features in the EUV (e.g., the H II 30.4 nm line) are optically thick and self-absorbed due to the abundance of the lower state of the transition. By contrast, most hot coronal features in the soft X-ray region, typically highly ionized metallic lines, are optically thin, and hence are not subject to limb absorption effects [Chamberlin et al., 2008]. The dependence of ionospheric responses on flare location (CMD value) also comes from the flare location effect on solar EUV enhancements [e.g., Zhang et al., 2002; Tsurutani et al., 2005; Mahajan et al., 2010; Qian et al., 2010].

4. Conclusion and Remarks

[19] On the basis of high sensitivity accelerometers on board the CHAMP satellite and GRACE satellite, several studies [e.g., Sutton et al., 2006; Liu et al., 2007] show some
obvious enhancements in neutral density during the two great solar flares on 10/28/2003 and 11/04/2003. However, other flare events have not been studied in detail. In this study, neutral density data derived from observations made by the CHAMP and GRACE satellites have been used to investigate the neutral density response to solar flares for all the X-class solar flares during 2001–2006.

[20] The observed results show the density response for X1–5 flares falls within the noise level in the thermosphere but there is significant neutral density response for X5+ flares. Then we carried out an analysis of the X5+ events to study the dependence of neutral density response on peak X-ray, modified peak X-ray with CMD, peak EUV, and time-integrated EUV, respectively. The results show a very poor correlation coefficient of 0.3 between ∆Nn and peak X-ray, but a much improved correlation coefficient of 0.85 between ∆Nn and modified peak X-ray with CMD, which means that same as the ionosphere, the thermospheric response to a solar flare also can be affected by solar flare location on the disk. This flare location effect mainly comes from the dependence of solar EUV flux on solar flare location, because the neutral density enhancement is highly related to the EUV variation. The correlation coefficient between ∆Nn and peak EUV is about 0.65. Furthermore, it reaches about as high as 0.91 for time-integrated EUV. The results show the neutral density response is highly related to the variation in EUV flux during a solar flare and its magnitude is mainly determined by time-integrated EUV flux.

[21] Our results show that with the exception of the great solar flares like (X17.2 October 28 2003 and X28 November 4 2003), the moderate X-class flares (X5+) also has a nonignorable effect on the thermosphere, with an average enhancement of 10 ~ 13% in neutral density at mid-low latitudes within about 4 h after solar flare onset. In addition, changes in the density and composition of the thermosphere can significantly affect the ionospheric density [Fuller-Rowell et al., 1994; Pawlowski and Ridley, 2009]. Tsunrutan et al. [2005] reported that there is a long duration ionospheric response with ∼3 h enhancements in TEC during X17.2 October 28 2003 solar flare, which might be the long time variation in neutral density. The study on coupling between the ionosphere and thermosphere during a solar flare can be done by more synchronous observation for the ionosphere and thermosphere, as well as by modeling. Pawlowski and Ridley [2009] modeled the ionospheric responses to the solar flare on October 28 2003 by using a coupled ionosphere-thermosphere model; the simulated results show that the ionospheric responses can be affected due to the thermospheric perturbations during the solar flare.

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