The longitudinal variation of the daily mean thermospheric mass density

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[1] This study uses the GRACE (Gravity Recovery And Climate Experiment) and CHAMP (CHAllenging Minisatellite Payload) accelerometer measurements from 2003 to 2008. These measurements gave thermospheric mass densities at ~480 km (GRACE) and ~380 km (CHAMP), respectively. We found that there are strong longitude variations in the daily mean thermospheric mass density. These variations are global and have the similar characteristics at the two heights under geomagnetically quiet conditions (Ap < 10). The largest relative longitudinal changes of the daily mean thermospheric mass density occur at high latitudes from October to February in the Northern Hemisphere and from March to September in the Southern Hemisphere. The positive density peaks locate always near the magnetic poles. The high density regions extend toward lower latitudes and even into the opposite hemisphere. This extension appears to be tilted westward, but mostly is confined to the longitudes where the magnetic poles are located. Thus, the relative longitudinal changes of the daily mean thermospheric mass density have strong seasonal variations and show an annual oscillation at high and middle latitudes but a semiannual oscillation around the equator. Our results suggest that heating of the magnetospheric origin in the auroral region is most likely the cause of these observed longitudinal structures. Our results also show that the relative longitude variation of the daily mean thermospheric mass density is hemispherically asymmetric and more pronounced in the Southern Hemisphere.

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1. Introduction

[2] Space borne observations show that there are variations in thermospheric mass densities at various spatial and temporal scales. One of these variations is the longitude/UT variation of the thermospheric mass density in which the change of the density is a repeatable cycle with a period of 24 h or through 360° in longitude. This longitude/UT variation of the thermospheric mass density has been attributed to heating in the aurora region, in the form of Joule heating and particle heating, and was noted by a number of researchers [e.g., Hedin and Reber, 1972; Hedin et al., 1979; Hedin and Carignan, 1985; Hedin, 1991; Forbes et al., 1999]. They showed that the longitude variations of the thermospheric density are stronger near the magnetic poles and vary with magnetic local time. On the other hand, the thermospheric mass density can also vary with longitude and UT or LT because of the influence of tidal waves. In recent years, there have been some studies on the relationship between the longitudinal variations of the atmospheric density and the tides in the thermosphere [e.g., Forbes et al., 2003, 2011; Oberheide et al., 2009, 2011, and references therein].

[3] Therefore, the satellite observed longitude/UT variations of the thermospheric mass density are probably a mixture of tides and the longitudinal variation induced by Joule and particle heating in the auroral region. However, most of these previous studies of the longitude variation of the thermospheric mass density did not separate the effect of heating in the auroral region from that of the propagating tides. It is thus necessary to remove the tidal effect by performing a daily mean of the satellite observed mass densities and to investigate the effect of heating in the auroral region on the background thermospheric density, which is the main subject of the current study.

[4] Laux and von Zahn [1979] used data from the gas analyzer on board the Esro 4 satellite from November 1972 to April 1974 to study the average longitude variations of N₂, O, He, and Ar densities under geomagnetically quiet conditions. They also found that there is a persistent longitudinal variation of the thermospheric composition and the strongest longitudinal deviations of these densities occur in the vicinity of the magnetic poles. However, the seasonal variation of this longitudinal structure was not given and tidal effects were not clearly separated out in this study either.

[5] In this work, we focus on answering the following two questions that have not been addressed before: (1) what is...
the global structure of the longitudinal variation of the thermospheric density induced by heating in the auroral region when the effects of tidal waves are removed? and (2) what are the seasonal variations of this longitudinal structure? We use thermosphere total mass densities inferred from the accelerometer measurements made by the GRACE and CHAMP satellites from 2003 to 2008 for our studies. The tidal effects on the longitudinal variations are removed because the daily mean thermospheric mass density is used in our data analysis. The rest of the paper is organized as follows: section 2 presents the data set and analysis method. The results are shown in section 3. Section 4 gives a discussion and the findings of this study are summarized in the last section.

2. Data Set and Analysis Method

[6] The GRACE satellite was launched on 17 March 2002. The GRACE’s orbit is almost circular and near polar (inclination is 89°). The initial altitude of GRACE was about 500 km, it decreased to about 475 km in 2008. The CHAMP satellite was launched on 15 July 2000 into an almost circular, near polar orbit (inclination is 87°) with an initial altitude of about 450 km. The altitude of CHAMP decreased gradually to about 330 km in 2008 because of the air drag. To remove changes of atmospheric densities introduced by altitude variations of the satellites, the mass densities obtained from GRACE and CHAMP accelerometer measurements are normalized using the NRLMSISE-00 model [Picone et al., 2002] to fixed reference heights of 480 and 380 km [Liu et al., 2007; Ma et al., 2010], respectively.

[7] For each latitude, the atmospheric density can be expressed as follows:

\[
\rho(\lambda, t) = \bar{\rho} + \Delta \rho(\lambda) + \sum_{i=1}^{4} \sum_{j=-8}^{8} A_{ij} \cos[i \omega_0(t-t_0) + j \lambda],
\]

where \(\lambda\) and \(t\) are longitude and local time, respectively. The first term on the right side of the above equation, \(\bar{\rho} = \frac{1}{48\pi} \int_{0}^{2\pi} \int_{0}^{24} \rho(\lambda, t) d\lambda dt\), is the zonal mean of the daily mean thermospheric mass density. The second term is the longitude variation of the daily mean thermospheric mass density,

\[
\Delta \rho(\lambda) = \frac{1}{24} \int_{0}^{24} \rho(\lambda, t) - \bar{\rho} dt
\]

This longitude variation of the daily mean thermospheric mass density does not change with time and is not related to tides. The third term on the right side of equation (1) is the migrating (\(j = 0\)) and nonmigrating (\(j \neq 0\)) tides. \(\omega_0 = 2\pi/24\) is the frequency of the 24 h wave. \(i (=1,2,3,4)\) denotes a subharmonic of a solar day, which represents 24, 12, 8, and 6 h waves, respectively. \(j (=\ldots -2, -1, 0, 1, 2, \ldots)\) is the zonal wave number. \(A_{ij}\) and \(t_0\) are the amplitude and phase of each tidal mode \((i, j)\). The zonal mean of the thermospheric mass density for each latitude,

\[
\bar{\rho}_i(t) = \frac{1}{2\pi} \int_{0}^{2\pi} \rho(\lambda, t) d\lambda = \bar{\rho} + \sum_{i=1}^{4} A_{i0} \cos[i \omega_0(t-t_0)],
\]

is the combination of the zonal daily mean mass density and the migrating tides, because the nonmigrating tides are removed, and the longitude variation of the daily mean thermospheric mass density is also removed because of

\[
\frac{1}{2\pi} \int_{0}^{2\pi} \Delta \rho(\lambda) d\lambda = 0.
\]

[s] There are only two local times in the daily observations of the GRACE and CHAMP satellites. These two local times of descending (\(t_0\)) and ascending orbits (\(t_d\)) are separated by 12 h. The average between the zonal mean mass densities of descending and ascending phases of the satellite orbits (marked as \(\Re\)) is

\[
\Re = \frac{1}{2} [\bar{\rho}_y(t_d) + \bar{\rho}_x(t_d)] = \bar{\rho} + \sum_{i=2,4} A_{i0} \cos[i \omega_0(t-t_0)].
\]

Where, \(\bar{\rho}_x(t_d) = \frac{1}{2\pi} \int_{0}^{2\pi} \rho(\lambda, t_d) d\lambda\) and \(\bar{\rho}_y(t_d) = \frac{1}{2\pi} \int_{0}^{2\pi} \rho(\lambda, t_d) d\lambda\) are the zonal mean mass densities measured in the descending and ascending orbits, respectively. The diurnal and terdiurnal tides are removed when the average between the descending and the ascending densities is made. Thus, we can obtain the relative difference between the total mass density and \(\Re\),

\[
\frac{\rho(\lambda, t) - \bar{\rho}}{\Re} - 1 = \frac{1 - \sum_{i=2,4} A_{i0} \cos[i \omega_0(t-t_0)]}{\bar{\rho}} - 1
\]

\[
\simeq \frac{\rho(\lambda, t) - \bar{\rho}}{\bar{\rho}} - \sum_{i=2,4} \sum_{j=-8}^{8} A_{ij} \cos[i \omega_0(t-t_0)]
\]

where \(\bar{A}_{ij} = A_{ij}\) is the relative amplitudes of the tides, which are defined as the ratios between the amplitudes of the tides and the zonal mean of daily mean density. In order to remove the contribution of the tides, a 24 h average of the above equation is made. By using equation (2), we can obtain

\[
\frac{1}{24} \int_{0}^{24} \left[ \frac{\rho(\lambda, t)}{\Re} - 1 \right] dt = \Delta \rho(\lambda) - \frac{1}{2} \sum_{i=2,4} \sum_{j=-8}^{8} \bar{A}_{ij} \cos(j \lambda + \Delta \phi_{ij})
\]

The first term on the right side of the above equation is the relative longitudinal variation of the daily mean mass density, which is defined as the ratio between the longitudinal variation of the daily mean mass density and the zonal mean of daily mean mass density. The second term on the right side of the above equation is due to

\[
\frac{1}{24} \int_{0}^{24} \{ \bar{A}_{ij} \cos[i \omega_0(t-t_0)] \bar{A}_{ij} \cos[k \omega_0(t-t_0) + j \lambda] \} dt
\]

\[
= \left\{ \begin{array}{ll}
0, & k \neq i \\
\frac{1}{2} \bar{A}_{ij} \bar{A}_{ij} \cos(j \lambda + \Delta \phi_{ij}), & k = i
\end{array} \right.
\]

Where, \(\Delta \phi_{ij} = i \omega_0(t_0 - t_0)\). Therefore, the second term of the right side of equation (6) mainly comes from the
contributions of semidiurnal tides and 6 h tides. Now, we estimate the contribution of this term. Migrating diurnal tides are the strongest tides in the thermosphere, and the migrating semidiurnal tides are the second strongest ones. Both are generally much larger than nonmigrating tides. Forbes et al. [2011] showed that the NRLMSISE-00 empirical model can reproduce the outline of the migrating tides, by comparing tides obtained from CHAMP and GRACE observations with those derived from the NRLMSISE-00 model, but the model underestimates the amplitude of the migrating semidiurnal tide during December–January by about 50%. Therefore, we use the NRLMSISE-00 model to estimate the relative amplitude of the migrating semidiurnal tide of the thermospheric mass density using the same method as that in Forbes et al. [2011], which is about 20% at low latitudes. Given that NRLMSISE-00 may underestimate the amplitude of the migrating semidiurnal tide [Forbes et al., 2011], we increase the relative amplitude of the migrating semidiurnal tide from 20% to 30% to estimate the maximum possible effect of the second term on the right-hand side of equation (6) on the longitudinal variation of the daily mean thermospheric mass density. Note that for the $j = 0$ case, the second term on the right-hand side of equation (6) is a constant and does not change with longitude. Thus, it has no effect on the longitude variation of the daily mean thermospheric mass density. The relative amplitudes of the nonmigrating tides ($j \neq 0$) are usually less than 10% [e.g., Oberheide et al., 2009, 2011]. For instance, according to theoretical estimations and CHAMP observations, the maximum relative amplitudes of the nonmigrating diurnal tide (DE3) and the nonmigrating semidiurnal tide (SE2) are about 6% in the low and middle latitude region [Oberheide et al., 2009, 2011] at the altitude of the CHAMP satellite. Therefore, the contribution of the second term of equation (6) (product of migrating semidiurnal tides and nonmigrating tides) is less than 1%. Note that these estimated values of the second term on the right-hand side of equation (6) are for low and middle latitudes. The amplitude of the migrating semidiurnal tide is very small in the high latitude region (c.f. Figures 7 and 8 in Forbes et al. [2011]). For instance, at the CHAMP altitude, the NRLMSISE-00 model predicts that the maximum relative amplitudes of the semidiurnal tide in thermospheric mass density are about 9% at 65° and 2% at 80° for the winter hemisphere. Thus, the effect of the second term of equation (6) should be much smaller at high latitudes, and can be neglected. Furthermore, the relative amplitude of 6 h migrating tide is also very small (~3%), its contribution is less than 0.1% and can also be ignored. Therefore, equation (6) can be used to estimate the relative longitude variation of the daily mean thermospheric mass density for each latitude by neglecting the second term on the right-hand side:

$$\frac{\Delta p(\lambda)}{\rho} \approx \frac{1}{24} \int_{0}^{24} \left[ \frac{p(\lambda, t)}{\rho} - 1 \right] \, \mathrm{d}r. \quad (7)$$

Thus, equation (7) gives the relative longitudinal variations of the daily mean thermospheric mass density with most of the effects of migrating and nonmigrating tides being removed. Thus, the obtained daily mean thermospheric mass density does not change with either local time or universal time.

[9] A full 24 local time coverage by the GRACE and CHAMP observations needs about 160 and 130 d, respectively. In this work, for each satellite, we combine its quiet-time ($Ap < 10$) observations from 2003 to 2008 into 1 yr. In Figure 1, we take GRACE and CHAMP observations under geomagnetically quiet conditions ($Ap < 10$) in latitude bins of $\pm 70^\circ \pm 5^\circ$ and $0^\circ \pm 5^\circ$ at the equator and a longitude bin with a width of $10^\circ$ during June and July as examples to illustrate the composite local time coverage by the satellites. It is evident that a 2 month window is sufficient to ensure the 24 h local time coverage. Therefore, a 2 month window is used to obtain the 24 h average.

3. Results

[10] In this study, we use data under geomagnetically quiet conditions ($Ap < 10$). The 2 month averaged global distributions of the relative longitudinal variation of the daily mean thermospheric mass density of January–December, February–March, April–May, June–July, August–September, and October–November obtained from the GRACE observations are given in Figure 2. There is an evident positive peak of the relative variation of the daily mean mass density (high thermospheric mass densities) at high latitudes in each hemisphere for all seasons. In the Northern Hemisphere, the longitude of the positive peak is around $240^\circ$–$300^\circ$E. The same peak occurs around $100^\circ$–$180^\circ$E in the Southern Hemisphere. They are located in the aurora zone centered around the magnetic poles (white crosses in the figure). More precisely, these positive peaks occur near the longitudes and equatorward of the magnetic poles in each hemisphere.

[11] Figure 2 shows clearly that there are strong seasonal variations in the longitude variation of the daily mean thermospheric mass density. The longitude variations are smallest in the summer hemispheres (December–January in the Southern Hemisphere and June–July in the Northern Hemisphere). At high latitudes of the winter hemisphere, there are very strong longitude variations in thermospheric mass densities, which last several months around the winter solstice for each hemisphere.

[12] In December–January the largest peak of the relative longitude variation of the daily mean mass density is located near the northern magnetic pole, which is 11%. During June–July, the largest peak of the relative deviation of the daily mean mass density is 11%, which is located near the southern magnetic pole. The maximum positive peak of the relative longitude variation of the daily mean mass density for the entire year is 15.2%, which is near the southern magnetic pole during April–May (Figure 2c).

[13] Figure 3 gives the result from the CHAMP observations. Comparing between Figures 3 and 2, we find that the characteristics of the longitude variation of the daily mean mass density at the two altitudes are very similar, but the relative deviation of the daily mean mass density at the CHAMP altitude is smaller than that at the higher altitude of the GRACE. The maximum of the relative deviation of the daily mean mass density at the CHAMP altitude for the entire year is about 11.5%, occurring also during April–May in the Southern Hemisphere.
Figure 4 shows seasonal variations of the positive maximum of the relative longitudinal variation of the daily mean thermospheric mass density at GRACE and CHAMP altitudes, respectively. The figure illustrates that the maxima of the longitude variation of the daily mean mass density take place in winter at high latitudes in each hemisphere (from October to February in the Northern Hemisphere and from March to September in the Southern Hemisphere). Thus, at middle and high latitudes in both hemispheres there is an evident annual component in this longitude variation of the daily mean mass density. Figure 4 also shows that there is a strong semiannual component in the longitudinal variation of the daily mean thermospheric mass density around the equator, with positive peaks occurring near June/July and December/January, respectively.

4. Discussion

There are three major sources for the energy input to the thermosphere: solar EUV radiation, Joule dissipation, and kinetic energy deposition by auroral particle precipitation. There is an obvious difference between the solar EUV radiation heating and Joule and particle precipitation heating at high latitudes. The solar EUV radiation heating is global in scale and modulated by seasonal and local time variations of the solar zenith angle and the Sun-Earth distance. The daily
average of this energy source only varies with latitude and season, but it is uniform for all longitudes. Thus, to a good approximation the effect of solar EUV radiation on the longitudinal structure of the daily mean mass density is negligible. On the other hand, energy deposition by Joule heating and particle precipitation is localized. Joule heating and particle precipitation can vary significantly with magnetic local time, solar wind, and other geophysical conditions. However, their daily averaged patterns are mostly limited to the regions around the north and south magnetic poles. The global total amount of Joule heating and particle heating is evidently much smaller than solar EUV radiation heating during quiet periods [Knipp et al., 2004]. However, in the auroral region at high latitudes, solar zenith angle is great and solar EUV heating is not as large as that at middle and low latitudes. Thus, Joule heating and particle heating become comparable to the energy deposited by solar EUV radiation heating under geomagnetically quiet or moderate active conditions [Thayer and Semeter, 2004]. During the geomagnetic active period, Joule heating and particle heating can be much larger than solar EUV radiation heating in the auroral region. Jee et al. [2008] showed by model simulations that Joule heating rate in the thermosphere could reach about 5.0e-3 K/s, or 430 K/d during a storm event. The total heating rate in the thermosphere is about 900 K/d [Roble, 1995]. Therefore, in the high latitude region, Joule and particle heating are

Figure 2. The global distribution of the relative longitude variation of the daily mean thermosphere mass density observed by the GRACE satellite. Left and right panels are the polar view of the longitudinal variations of the daily mean thermospheric mass density in the Southern and Northern hemispheres, respectively, while middle panels give a global view of these variations. White crosses are the positions of the north and south magnetic poles, respectively.
very important heating sources for the thermosphere besides solar UV radiation.

[16] The south and north magnetic poles locate at about 64°S, 140°E and 81°N, 110°W in the geographic coordinate system, respectively. This means that auroral heating (Joule dissipation and particle heating) is asymmetric in geographic latitude and longitude. In addition, unlike solar EUV radiation heating, which becomes very weak, or even disappears at the polar night, during the winter solstice condition in each hemisphere, energy input to the upper atmosphere by auroral heating still exists under this condition, although its magnitude depends on the strength of geomagnetic activity.

[17] We showed in the previous section that there are three salient features in the global structure of the relative longitude variation of the daily mean thermospheric mass density. The first one is that the relative longitude variation of the daily mean mass density reaches maximum at high latitudes of the winter hemisphere, which can last several months. It is very weak in the summer hemisphere. This is probably caused by the fact that Joule heating and particle heating in the auroral region are much weaker than the solar EUV radiation heating in the summer for geomagnetically quiet conditions [Knipp et al., 2004] considered in the present work. Whereas in the winter hemisphere at high latitudes the solar EUV radiation heating becomes weak, the relative contribution of Joule heating and particle heating to the upper atmospheric energetics becomes significant, and is larger than in the summer. Thus, the relative longitudinal changes in the daily mean mass density is more pronounced in months around the winter solstice. Note that even under geomagnetically quiet conditions there is still a large amount of Joule heating and particle heating deposited in the thermosphere at high latitudes to affect the behavior of the thermosphere-ionosphere system [Knipp et al., 2004; Deng et al., 2011]. From Figure 4, we can also see that the longitude variation of the daily mean mass density reaches maximum at high latitudes before and after the winter solstice. This might be related to the fact that there

Figure 2. (continued)
is a clear semiannual variation of electron densities that peaks at equinox [e.g., Zou et al., 2000] and that Joule heating is determined by ionospheric electron densities and electron fields. Therefore, before and after the winter solstice, the relatively high electron densities can produce relatively high Joule heating, but at the same time solar UV radiation heating decreases as the solar zenith angle becomes large. This can probably cause the relative longitude variation of the daily mean mass density to reach maxima at high latitudes before and after the winter solstice, for instance, in April-May in the Southern Hemisphere. The exact mechanism for this feature, however, needs further investigation.

[19] The second feature is that the longitude variation of the daily mean thermospheric mass density in the southern winter is evidently stronger than that in the northern winter. This is evident in the plot of the maxima of the longitude variation of the daily mean thermospheric mass densities (Figure 4). The highest relative longitudinal variations occur clearly in April-May at the high latitudes of the Southern Hemisphere for both GRACE and CHAMP observations. This hemispheric asymmetry is probably caused by the difference of the magnetic pole positions relative to the geographic poles between the Northern and Southern hemispheres. The northern magnetic pole is closer to the northern geographic pole than the southern magnetic pole is to the southern geographic pole. The latitude of the southern magnetic pole is near 64°S, which is far from the southern geographic pole. Whereas, the northern magnetic pole is at about 81°N, which is near the northern geographic pole. Therefore, the heating in the auroral region in the Southern Hemisphere is more conductive to produce the longitude variation of the daily mean mass density than it is in the Northern Hemisphere. Furthermore, because the southern magnetic pole is located more toward midlatitudes, the auroral region in the Southern Hemisphere has relatively smaller solar zenith angles than the auroral region in the Northern Hemisphere. Thus, ionospheric electron densities and conductivity, to which Joule heating is directly proportion, are larger in the auroral region of the Southern Hemisphere. It also appears that the longitudinal structure locates farther away from the magnetic pole in the Northern Hemisphere. The exact cause of this interesting phenomenon is not clear and need further investigation. It is probably related to the

Figure 3. The global distribution of the relative longitude variation of the daily mean thermosphere mass density observed by the CHAMP satellite. White crosses are the positions of the north and south magnetic poles, respectively.

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smaller displacement of the magnetic pole from the geographic pole in the Northern Hemisphere. The region near the northern geographic pole is also heated by Joule heating, which makes the relative longitudinal variation near the northern geographic pole less evident. First principles, coupled with thermosphere ionosphere modeling, will be employed in future studies to investigate the longitudinal structure of the daily mean thermosphere mass density reported in this paper, and also its latitudinal changes.

The third feature of the longitude variation of the daily mean mass density is that it extends from high latitude to low latitude regions, even into the opposite hemisphere. This extension is mostly limited to the longitudes of the magnetic poles in each hemisphere, but tends to be tilted westward. This expansion pattern is probably due to the additional thermospheric circulation from high latitudes toward the equator induced by the heating in the auroral region and the westward turning of this equatorward meridional circulation by the Coriolis effect. Figure 4 shows that the extension of high-density regions from the two hemispheres produces two density peaks around the equator. Thus, at middle and high latitudes, there is only one peak of the relative longitude variation of the daily mean mass density in a year, and the longitudinal variations of the daily mean thermospheric mass density has a strong annual component. Whereas there are two peaks around the equator in a year, which have amplitudes of about 5%. Therefore, around the equator there is a strong semiannual component in the longitudinal variation of the daily mean mass density with positive peaks occur near June/July and December/January.

5. Summary

In this paper, we used thermosphere mass density data inferred from the accelerometer measurements made by the GRACE and CHAMP satellites to study the longitude structure of the daily mean thermospheric mass density under the quiet geomagnetic condition. Daily mean is performed on these data so that the effects of tides are removed. The results show that the thermospheric mass density is not uniform in the zonal direction, and there are strong longitude variations at all latitudes. The maximum of the daily mean mass density is always around the aurora zone, which suggests that these longitudinal variations are most likely the result of Joule and particle heating in the auroral region. The results also show that the relative longitude variation of the daily mean mass density relative to the zonal mean of the daily mean mass density reaches maximum at the high latitude in several months around winter in each hemisphere. These longitudinal variations in the daily mean thermospheric mass density are also obviously stronger in the Southern Hemisphere than they are in the Northern Hemisphere. The longitude variations of the daily mean thermospheric mass density, however, are not restricted to the high latitude regions; rather they are a global feature. They extend to lower latitude regions, tend to be tilted westward, and have similar characteristics at the two different heights where the mass density data were observed by the GRACE and CHAMP satellites between 2003 and 2008. Thus, the longitudinal variations of the daily mean thermospheric mass density have strong seasonal variations and show an annual oscillation at high and middle latitudes but a semianual oscillation around the equator.

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