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Climatology of the Equatorial Thermospheric Mass Density Anomaly

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Abstract.
The equatorial anomaly is an interesting and important feature of the Earth’s thermosphere-ionosphere coupling in tropical regions. It is an anomalous latitudinal distribution found in both the ionized and unionized part of the atmosphere. Its equinox configuration consists of a minimum near the dip equator flanked by two maxima on both sides. The thermospheric counterpart of this anomaly, often referred to as equatorial ionization anomaly (EIA), has long been recognized since the 1930s. However, its thermospheric counterpart was only to be glimpsed by the Dynamic Explorer 2 satellite in the 1970s. A global picture of it has been rather recently revealed by the CHAMP satellite in 2005. In this paper, we complement previous studies by investigating the climatology of the equatorial mass anomaly (EMA) in the thermosphere using 4 years of CHAMP measurements. Our analysis has revealed strong variation of the EMA with season and solar flux level. The EMA structure is most prominent around equinox, with a crest-to-trough ratio about 1.05 for F10.7=150. Near solstices, it is asymmetric about the dip equator. The density crest attains maximum 1–2 hrs earlier and reaches higher values in the summer hemisphere than in the winter hemisphere. The density in EMA regions varies semiannually, with maxima near equinoxes. The latitudinal locations of the EMA crests undergo a seasonal variation, obviously following the movement of the sub-solar point. The EMA structure has also been found to become more pronounced at higher solar flux levels. Both the location and magnitude of the EMA crests closely follow those of the EIA in corresponding seasons and solar flux levels, hence demonstrating strong plasma-neutral interaction. Furthermore, two seasonal asymmetries clearly present in the globally averaged density, with the density in March/December being ~15 – 20% higher than that in September/June.

1. Introduction
The Earth’s thermosphere has been known to be coupled with the ionosphere. Among various features, the equatorial anomaly is a very interesting and important one, revealing strong neutral-plasma interaction. This anomaly, whose equinox configuration shows a minimum near the dip equator flanked by two maxima on both sides, has long been recognized in the ionospheric electron density and referred to as the Appleton anomaly or the Equatorial Ionization Anomaly (EIA). Its formation has been attributed to a fountain effect, mainly driven by the large-scale eastward electric field at low latitudes [e.g. see review of Rishbeth, 2000, and references therein]. A similar anomaly has been identified in the thermosphere as well, first in the composition N₂ [Philbrick and Mclsaac, 1972; Hedin and Mayr, 1973], then in the neutral temperature and wind [Raghavarao et al., 1991, 1993], and recently in the total air mass density [Liu et al., 2005]. These anomalous latitudinal distributions in both the ionized and unionized part of the atmosphere demonstrate a strong ionosphere-thermosphere coupling at low and middle latitudes.

The EIA structure has been investigated extensively in the past, and its morphology is now largely known [e.g. Thomas, 1968; Sharma and Hewens, 1976; Walker et al., 1994; Huang and Cheng, 1996; Tsai et al., 2001; Liu and Wan, 2001; Liu et al., 2006b]. In contrast, its thermospheric counterpart has so far lacked sufficient study. This may partly be due to the fact that neutral particles are more difficult to probe than the charged ones. Mayer et al. [1974] briefly discussed the anomaly in individual atmospheric compositions around equinox and June solstice using a numerical model. The two density crests of this anomalous structure were shown to be asymmetric at June solstice, with higher density in the winter hemisphere. However, these predictions and proposed mechanisms have so far not been validated by observations. Utilizing one year observations from the satellite CHAMP, Liu et al. [2005] obtained a global picture of the equatorial air mass density anomaly (abbreviated as EMA in the following). This EMA structure has been observed to generally appear after 10 local time (LT) and persists till ~ 19–21 LT depending on season, being most prominent between 11–16 LT. Its formation was speculated to be caused by ion drag and charge-exchange released chemical heating, both of which are related to the EIA structure. However, this hypothesis could not be examined from a climatological point of view due to limited data. In addition, the Mass Spectrometer Incoherent Scatter (MSIS) model [Hedin et al., 1991], which is widely used for satellite orbital predictions, is currently unable to reproduce the EMA structure either [Liu et al., 2005]. Therefore, further studies clarifying the climatology of the equatorial thermospheric anomaly are highly needed for both theoretical and practical purposes. As a following-up study of Liu et al. [2005], we investigate in this pa-
per the EMA variations with season, geomagnetic activity and sol-
lar flux levels by using 4 years of CHAMP measurements during
2002–2005. Given the hypothesis of Liu et al. [2005], we would
expect these EMA climatological variations to closely follow those
of the EIA.

2. Methodology and Data Selection

The CHAMP satellite was launched on July 15, 2000 into a
near-circular orbit with an inclination of 87.3° and an initial
altitude of 456 km. The precessing rate of its orbital plane is
1.5°/day. Among various scientific instruments onboard, a tri-axial
accelerometer effectively probes the in-situ air drag, which yields
estimates of the air mass density with an accuracy of 1 × 10^{-14} kg m^{-3}
at a sample rate of 0.1 Hz (Level 2 data). The detailed proce-
dure for deriving the mass density from the CHAMP accelerome-
ther has been described in Liu et al. [2006a]. It improves the one
given in Liu et al. [2005] by effectively removing the influence
of cross-track wind on the derived density. In the present study,
we use measurements during 11–16 LT, where the EMA structure
is most prominent. These data are further classified into "quiet"
(Kp ≤ 2) and "moderate" (3 ≤ Kp ≤ 5) geomagnetic conditions
(the current 3-hour Kp values are used). Very active periods with
Kp > 5 are not analyzed due to possibly increasing error from in-
track winds and limited number of samples. The monthly mean is
then obtained for each activity level by averaging densities falling
into the 11-16 LT sector during each calendar month, for every 3
degrees in corrected geomagnetic (cgm) latitudes. By doing so,
we ignore the relatively small local time variation around noon
and focus on the long-term variations with season and solar cycle.
The number of satellite passes contributing to the average of each
month at the equator is shown in Figure 1. Owing to CHAMP’s
high inclination of 87.3°, the number of passes varies little with
lattitudes within ±60°. Density variations due to changes in or-
bital altitude have been removed before the averaging, via a nor-
malization to a common altitude of 400 km using the NRLMSIS
model [Picone et al., 2002]. Since CHAMP’s mean altitude at low
and middle latitudes varied within 412–360 km during the years
of 2002–2005 (see Figure 1), the normalization was applied within
one scale height. Therefore, errors caused by this procedure are
expected to be small (within 5% given a similar uncertainty in the
MSIS predicted scale height) and will not seriously compromise
the EMA climatology discussed below.

3. Longitudinal Variation of the Thermospheric Mass Density

Figure 2 depicts the noon-time mass density distribution in ge-
ographic coordinates at 400 km altitude, averaged over calendar
months of February–April. Density variations due to solar flux lev-
els have been removed by normalizing all density to a fix solar flux
level of F10.7 = 150 × 10^{-12} W m^{-2} Hz^{-1} using the NRLM-
SIS model (the "observed" values of F10.7 were used during this
procedure). The high density bands on both sides of the equator,
sandwiching a shallow minimum in between can be clearly rec-
ognized. In particular, these bands are well aligned with the dip
equator, which is indicated by the black line in the figure. This
alignment clearly demonstrates that the EMA structure is magneti-
cally controlled. Consequently, in geographic coordinates, the den-
sity experiences a strong longitudinal variation, particularly in the
−90°–0° longitude sector. However, when discussed in geomag-
netic coordinates, the longitudinal variation becomes less signifi-
cant. Therefore, we discuss in the following sections the climatol-
ogy of the longitudinally averaged EMA structures in geomagnetic
coordinates.

4. Climatological Variations

Figure 3 presents the mass density variation with geomagnetic
latitude and month of the year for two different geomagnetic ac-
tivity levels at a fixed solar flux level of F10.7 = 150. The black
lines depict the locations of the density peaks in corresponding
hemispheres. The x-axis represents month of the year, with Jan-
uary from 0–1, February from 1–2, etc. The interval of 12–13 is
a repetition of January, plotted here to show the density structure
in December and January more clearly. The seasonal mean of the
EMA structures are obtained by averaging densities falling within
the 60°–40° longitude band and shown in Figure 4. These figures reveal the seasonal and geo-
磁场感应的不均匀性，以及它们在不同季节和太阳活动期的变化。当太阳活动处于平静期（Kp ≤ 2）时，密度的月平均值被进一步分类为“平静”（Kp ≤ 2）和“中等”（3 ≤ Kp ≤ 5）磁活动条件。（此处使用3小时Kp值）。很活跃的时期（Kp > 5）不进行分析，因为这些条件下的地球表面风可能会显著影响密度。每月的平均值通过将密度落入11-16 LT（地方时）区间内的数据进行平均，对每个活动水平按3°的磁经度进行改正。由于CHAMP的高倾角（87.3°），在低和中纬度，经过密度的平均后，密度在±60°的范围内变化不大。密度变化是由于变化在轨道高度的去除，通过将所有密度归一化到400 km的NRLMSIS模型（“观测”值的F10.7值用于此过程）。通过该方法，误差被控制在5%以内，且不会显著地影响EMA的 climatology。下文将讨论。

3. 长度方向的热层质量密度的变

图2展示了日中时的质量密度分布，在地理坐标系中，在400 km的高度上，平均值是根据2月到4月的平均值计算得出的。太阳磁场对密度的影响已被去除，使用F10.7 = 150 × 10^{-12} W m^{-2} Hz^{-1}进行归一化，使用NRLMSIS模型计算得到的“观测”值的F10.7。因为CHAMP的平均高度在低和中纬度范围内变化较大，即412–360 km，所以归一化后的密度值在这些区域变化不大。因此，误差在5%以内，不会显著影响到EMA的 climatology。下文将讨论。

4. 气候学变化

图3显示了质量密度随经度和月变化的分布。对于两种不同的磁活动水平，在固定太阳活动的F10.7=150条件下，黑色线条表示密度峰值的位置。x轴为年份的月份，从1月到13月，其中12月到1月重复，以显示12月和1月的密度结构。图3和4显示了季节性和磁场感应的不均匀性，以及它们在不同季节和太阳活动期的变化。当太阳活动处于平静期（Kp ≤ 2）时，密度的月平均值被进一步分类为“平静”（Kp ≤ 2）和“中等”（3 ≤ Kp ≤ 5）磁活动条件。（此处使用3小时Kp值）。很活跃的时期（Kp > 5）不进行分析，因为这些条件下的地球表面风可能会显著影响密度。每月的平均值通过将密度落入11-16 LT（地方时）区间内的数据进行平均，对每个活动水平按3°的磁经度进行改正。由于CHAMP的高倾角（87.3°），在低和中纬度，经过密度的平均后，密度在±60°的范围内变化不大。密度变化是由于变化在轨道高度的去除，通过将所有密度归一化到400 km的NRLMSIS模型（“观测”值的F10.7值用于此过程）。因为CHAMP的平均高度在低和中纬度范围内变化较大，即412–360 km，所以归一化后的密度值在这些区域变化不大。因此，误差在5%以内，不会显著影响到EMA的 climatology。下文将讨论。

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the density maximum in September–October seems to peak at earlier time with increasing geomagnetic levels, being near the end of September under disturbed time in comparison to October under quiet conditions.

4.3. The Solar Flux Variation

The EMA structure has also been found to become more pronounced at higher solar flux levels. An example is shown in Figure 5 for equinoxes case. It presents the average EMA profile at three different F10.7 levels. The number of contributing satellite passes for each F10.7 level are 875, 1054, and 594, respectively. Note that the y-axis range in each plot has been adjusted to show the latitudinal variation more clearly, but the scale remains the same. It is not difficult to notice that in addition to the general increase of the density with increasing F10.7 at all latitudes, the EMA double-hump structure becomes more distinct at higher F10.7 levels. The crest-to-trough difference increases from about $0.1 \times 10^{-12}$ kg m$^{-3}$ for $F_{10.7} < 100$ to over $0.4 \times 10^{-12}$ kg m$^{-3}$ for $150 \leq F_{10.7} \leq 200$. In addition, there is a trend for the EMA crests to move poleward with increasing F10.7. For instance, the crest center shifts from about $20\degree$F for $F_{10.7} < 100$ to $25\degree$F for $150 \leq F_{10.7} \leq 200$. Accompanying these changes in the EMA, the EIA structure varies in a similar manner as reflected in the electron density observed by CHAMP in corresponding conditions. The EIA structure grows more pronounced, with the crest-to-trough ratio increasing from $\sim 1.16$ to $\sim 1.24$. The crest center also moved poleward, from $\pm 10\degree$F for $F_{10.7} < 100$ to $\pm 15\degree$F for $150 \leq F_{10.7} \leq 200$.

5. Discussion

The above analysis of 4 years of CHAMP observations has confirmed many previously reported thermospheric features, like the semiannual variation and June-December asymmetry [e.g. Boulton, 1985; Jacchia and Slowey, 1968; King-Hele and Walker, 1969; Moore, 1983]. Furthermore, it has revealed valuable climatological features of the EMA, which could not be examined before due to limited observations. In the following, we compare these features with those predicted by numerical models or seen in the EIA, which is the ionospheric counterpart of the EMA.

5.1. Comparison with Model Predictions

Among various numerical models, the one by Mayr et al. [1974] seems to be the only reported model able to produce an equatorial anomaly in the thermosphere. Therefore, it is interesting to compare their predictions with the CHAMP observations presented above. Their model predicted an equatorial anomaly near 450 km altitude, which was obvious in the atmospheric composition of $[N_2]$, and weakly discernible in $[O]$. This anomalous structure was shown to be symmetric about the equator around equinox and asymmetric at June solstice, with higher density in the winter hemisphere. Since the atmosphere is dominated by $[O]$ and $[N_2]$ at altitudes above about 350 km, these structures in the composition should result in similar structures in the total mass density which can be approximated by $16[O] + 28[N_2]$. Comparing with the total mass density observed by CHAMP, we immediately notice the discrepancy between the prediction and observations at June solstice. The hemispheric asymmetry in the individual composition shown by the model leads to a higher total mass density in the winter hemisphere than in the summer hemisphere. However, CHAMP has observed the opposite, with higher density in the summer hemisphere (see Figure 4).

Furthermore, the model of Mayr et al. [1974] predicted a LT shift between the two density crests in two hemispheres at solstices, with the one in the winter hemisphere occurring 1–2 hrs earlier in LT than that in the summer hemisphere. To examine this feature, contour plots of the CHAMP observed density distribution over LT and geographic latitudes are presented in Figure 6. We see two EMA crests, which are at similar LT near equinoxes but phase-shifted near solstices. The EMA crest in the summer hemisphere tends to occur 1–2 hrs earlier than that in the winter hemisphere. This tendency in LT shift apparently disagrees with that predicted by the model. Therefore, the CHAMP observations do not seem to support the model predictions.

5.2. Comparison with Seasonal and Solar Flux Variation of EIA

The CHAMP observations have shown strong seasonal variations of the EMA structure. In particular, the locations of the EMA crests move poleward in local summer and equatorward in local winter, following the movement of the subsolar point. The EMA northern crest experiences a winter anomaly which does not exist in the southern crest. The thermospheric anomalies mentioned in the introduction have been speculated to be caused by the EIA [Hedin and Mayr, 1973; Raghavara et al., 1991; Liu et al., 2005]. Given this hypothesis, we would expect the climatological variation of the EMA to closely follow that of the EIA, particularly its location and magnitude. In the following, we examine this speculation by comparing with the seasonal and solar flux variations of the EIA.

The seasonal variation of EIA has been extensively investigated in many studies [e.g. Thomas, 1968; Sharma and Hewens, 1976; Tsai et al., 2001; Liu et al., 2006b]. Here we take the results of Tsai et al. [2001] about the total electron contents (TEC) for comparison. Using TEC from the Global Positioning System (GPS), they showed that the EIA high density crests move significantly equatorward in local winter, down to about $\pm 9\degree$ geographic latitudes. While in summer, the EIA density crests was found to shift towards higher latitudes. This seasonal movement of the EIA crests agrees well with that of the EMA as seen in Figure 3. Tsai et al. [2001] have also showed that the EIA northern crests experience a winter anomaly, but the southern crest does not. The same trend is observed in the EMA (see Figure 4). The EIA structure has also been known to be more pronounced at higher solar flux levels, with the peak-to-trough difference increases [e.g. Walker et al., 1994]. This behavior again resembles the EMA variation with solar flux levels, as seen in Figure 5.

Therefore, both the locations and magnitudes of the EMA crests closely follow those of the EIA in corresponding seasons and solar flux levels. This supports the argument that the EIA could lead to the EMA structure of the neutral atmosphere. The principle physical processes involved are likely to be the ion drag [Hedin and Mayr, 1973] and the chemical heating related to charge-exchange process [Fuller-Rowell et al., 1997]. The ion drag, which is larger at the EIA crest latitudes due to higher electron density, slows down the zonal wind hence the transport of energy and mass from the dayside thermosphere towards nightside. This can lead to higher thermospheric mass density in the crest regions. At the same time, chemical heating fueled by the charge-exchange between $O^+$ and $O_2$ or $N_2$ occurs when charged particles fall down along geomagnetic field lines [Fuller-Rowell et al., 1997]. It is especially effective in the E-region and the released energy is equivalent to a radiation at $\lambda \approx 806$ nm. Consequently, the thermospheric temperature increases and the atmosphere expands correspondingly. Since the footprints of the EIA crests in the E region are at about $\pm 20\degree$ magnetic latitudes, this chemical heating process seems to contribute to the latitudinal offset between EMA and EIA.

Superposed on the ion drag and chemical heating effect, the large-scale meridional wind circulation [e.g. Roble et al., 1987] may also influence the EMA formation. Being usually poleward at day and equatorward at night, the meridional wind may enhance the EMA structure by transporting energy and mass from the equator to middle latitudes at day and suppress it at night by opposite transportation. This regulation may have contributed to the termination of the EMA at night. Interestingly, as shown in Figure 6, the EMA seems to persist longer to $\sim 20\degree$ LT at equinox, but terminates earlier at solstices ($\sim 17/18$ LT). This tendency agrees with the switching time of the meridional wind, which has been found to occur around 20 LT at equinoxes but shift to earlier time at solstices [Kawamura et al., 2000]. However, we cannot evaluate this point.
directly here due to the lack of simultaneous meridional wind measurements from the CHAMP satellite. Another mechanism related to heating by precipitated energetic neutral atoms from the radiation belt was proposed by Tinsley [1981]. Such precipitation has been shown by Sorbo et al. [2006] to peak at the magnetic equator during quiet times, but to develop a second peak away from equator which can reach 35° magnetic latitude in the growth and main phase of magnetic storms. Consequently, if these precipitated neutral particles produce sufficient heating, it would lead to a density maximum at the equator under quiet conditions, and with a second density enhancement on both sides of the equator during magnetic storms. However, since the observed EMA under quiet conditions shows density minimum instead of maximum at the dip equator, such precipitation is unlikely to contribute to the EMA formation. The CHAMP observations thus seem to offer little supporting evidence for this proposed mechanism.

Finally, we would also like to add a few words about the equinox asymmetry in the thermospheric density. As described in section 4.2 and better seen in Figure 4, a clear equinox asymmetry exists in the thermospheric mass density, with higher values in March than in September at low altitudes. A similar trend has been recognized by Balan et al. [1998] in the daytime electron density near and above the F region peak using MU radar observations at middle latitudes (~35° N). They attributed this asymmetry to the meridional neutral wind, which was northward but ~40% (~20 m s⁻¹) weaker near March equinox in comparison to September equinox. This would increase the March equinox HmF₂ at a higher altitude, where the recombination rate is low, hence leads to higher electron density than at September equinox. Though the related physical processes may differ, we find this difference in the meridional wind may also be invoked to explain the equinox asymmetry in the thermospheric mass density observed by CHAMP. According to the “spoon mechanism” proposed by Fuller-Rowell [1998], a stronger meridional wind would lead to a stronger mixing of the atmosphere in September. This would increase the mean molecular mass, resulting in a reduced atmospheric scale height. Consequently, the thermospheric total mass density at a fixed altitude would become smaller in September in comparison to March. This equinox asymmetry has been observed by CHAMP to become stronger at higher geomagnetic activity levels (see Figure 4), hence may indicate a stronger equinox asymmetry in the meridional wind.

In summary, the EMA shows strong variation with season and solar flux levels. It is most prominent around equinox at high solar flux levels. The latitude variations of EMA crests closely follow those of the EIA, hence adding supporting evidence for the important role of EIA in the EMA formation through ion drag and chemical heating. However, previous studies have also shown that unlike the EIA which persists till postmidnight, the EMA structure becomes indiscernible at night [Liu et al., 2005]. This feature seems to apparently deviate from a simple EIA-EMA cause-effect relationship. Superposed on the EIA effect could be the regulation by the meridional wind. Blowing poleward/equatorward at day/night, it could enhance/suppress the EMA structure via meridional transportation and potentially contribute to the EMA termination at night. To reconcile various factors and also to understand their relative importance, simultaneous measurements of the meridional wind would be essential, and diagnostic runs with a coupled thermosphere-ionosphere model is also highly desirable.

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References


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Figure 1. Number of satellite passes contributing to the monthly means in Figure 3 for two different geomagnetic activity levels. The line on the top represents the satellite’s mean altitude in corresponding months.

Figure 2. Distribution of the dayside thermospheric mass density (in units of $10^{-12}$ kg m$^{-3}$) over geographic coordinates under quiet geomagnetic conditions for a solar flux level of F10.7=150. Smoothing was applied to emphasize only the large-scale variations. The black line indicates the dip equator. Note the high density bands on both sides of the dip equator.
Figure 3. The mass density (in units of $10^{-12}$ kg m$^{-3}$) variation with geomagnetic latitude and month of the year at 400 km altitude for a fixed solar flux level of F10.7=150. The black lines depict the locations of the density peaks in corresponding hemispheres. The x-axis represents month of the year, with January from 0–1, February from 1–2, etc. The interval of 12–13 is a repetition of January, making it easier to recognize the density structures in December and January.
Figure 4. The EMA latitudinal profiles at 400 km altitude for different seasons at a fixed solar flux level of F10.7=150. The profiles are averaged over February–April for March equinox (ME), August–October for September equinox (SE), May–July for June solstice (JS), and November-January for December solstice (DS).
Figure 5. The average latitudinal profiles of the neutral mass density and the electron density at 400 km for different solar flux levels around equinoxes. The profiles are averaged between 11–16 LT. Heavy lines: the neutral mass density; light lines: the electron density. The number of contributing satellite passes for three F10.7 levels are 875, 1054, and 594, respectively.
Figure 6. Distribution patterns of the thermospheric total mass density (in units of $10^{-12} \text{kg m}^{-3}$) over LT and geographic latitudes in different seasons under quiet geomagnetic conditions. A double-hump structure can be recognized after about 10 LT and before about 18–21 LT depending on season.