Three-peak ionospheric equatorial ionization anomaly: development, drivers, statistics

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ABSTRACT

In this work, we discuss such unusual observation as occurrence of three-peak ionospheric electron density structure in the dayside ionosphere. Based on our analysis of electron density data from CHAMP satellite during years 2001-2009, we find that the 3-peak density structure occurs occasionally in the local afternoon hours in summer hemisphere. We estimate that, depending on the solar activity, such events can occur in 1.3% to 4.2% of all dayside observations. The majority of events were detected during the period of solar minimum, which can be explained by stronger thermospheric winds action, which is the main driver of the third ionization peak occurrence. Analysis of 4 months of data from Swarm A and Swarm B satellites showed that, although not often, the 3-peak electron density structures can be clearly detected as high as at ~530km. Further, the NRL ionosphere model SAMI3 was used to determine if the 3-peak structure could be replicated. Although there was an indication of a 3-peak structure in several simulations, they were not as clear cut as the data suggesting the thermospheric winds play a critical role in their formation.

1. INTRODUCTION

It is known that the main feature of the dayside low-latitude ionosphere is the equatorial ionization anomaly, that is also referred to as plasma fountain. The EIA is created by the ExB drift that uplifts the equatorial ionospheric plasma to higher altitudes, and forms the ionization trough at the magnetic equator. The uplifted plasma, in turn, diffuses downward along magnetic field lines into both hemispheres assisted by the gravitational and pressure gradients, and forms two peaks of the plasma enhancements at about 10-15 degrees of latitude from the magnetic equator (the crests of the EIA). During geomagnetic storms, the plasma can be uplifted higher and the EIA crests can travel farther away from the equator.

Besides this “classic” dayside 2-peak EIA structure, it has recently been shown that strong geomagnetic storms can produce 3- or even 4-peak latitudinal structures in the daytime ionosphere (Valladares, 2013; Maruyama et al., 2016).

Maruyama et al. (2016) based on modeling of the December 2012 solstice ionospheric distribution, have shown that 3-peak density structure can occur even under geomagnetically quiet conditions due to the prevailing summer-to-winter thermospheric circulation. Further, Astafyeva et al. (2016) seem to be the first to present a statistical study of the occurrence of the 3-peak density structure in the electron density based on the analysis of 7 years (from 2003 to 2009) of the in situ data from CHAMP satellite. Analysis of the satellite observations confirmed that the three-peak density structure occurs sufficiently often during geomagnetically quiet time; their 7-year data set showed that the third ionization peak develops in the afternoon hours in the summer hemisphere at solstice periods.

While that first statistical study provided us with some interesting information, several questions remained opened: 1) dependence on geomagnetic activity; 2) whether the 3rd ionization peak can be clearly observed at higher latitudes. It is known that the EIA is the F-region feature, so that we do not expect to see this feature above, for instance, 400-450 km. The previous statistical study was based on 7 years of data from CHAMP satellite that changed its orbital height from ~420 km (in early 2003) to ~320 km (in late 2009). Therefore, it is of interest to analyze other data (for instance, earlier CHAMP years (2000-2002), when the satellite was at ~430-450 km), and/or include data from the recent ESA mission Swarm, which consists of 3 identical satellites flying at 460 km (Swarm A and C) and 530 km (Swarm B). In this work, we study these fundamental questions. For this purpose, we extend the period of statistics for the existing CHAMP measurements, as we add three more years of the enhanced solar activity (2001-2002). This would give more information on whether the 3-EIA peak structure, indeed, occur more often during low solar activity. In addition to this, we add several months of observations from Swarm A and Swarm B satellites (2014 and 2015).

2. RESULTS AND DISCUSSIONS

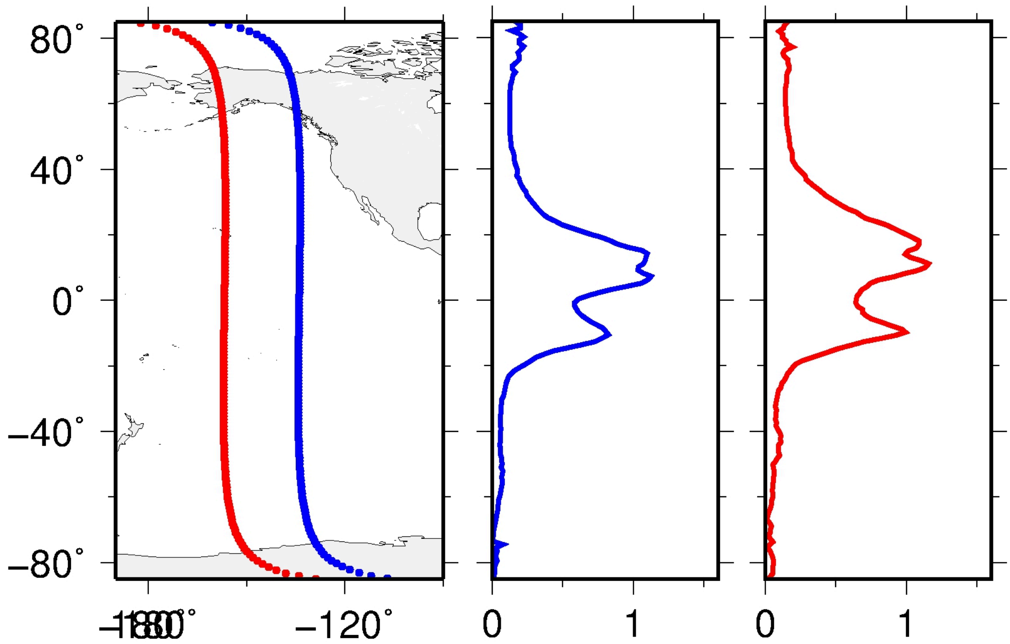

Figure 1. 3-peak density structures observed on 14 May 2009 by the CHAMP satellite at the altitude of ~320 km. The structures were observed during two consecutive passes from ~2.91UT to 3.66UT (blue curves), and from 4.43UT to 5.17UT (red curves). Panel on the left shows the two trajectories of the CHAMP satellite, the middle and the right-most panel show the Ne measurements during the corresponding CHAMP passes. Two density peaks occur in the northern hemisphere.

Figure 1 shows the examples of 3-peak density structures observed by CHAMP on 14 May 2009 at ~ 3-5 UT. To study the occurrence rate of the 3-peak density structure, we analyzed the whole Ne dataset from the Planar Langmuir Probe onboard CHAMP between May 2001 and December 2009. The results of our statistical analysis are shown in Figure 2. One can see that during years 2001-2004 and 2006 very few 3-peak events were detected by the CHAMP satellite, while many more events occurred in 2005 and in 2007-2009 (Figure 2a). In agreement with previous observations, the events mostly occur during the local afternoon hours in the summer hemisphere.

We estimate that the 3-peak EIA structure occurred in ~1.3% of dayside observations in 2001-2004 and 2006, and in about ~4.2% of the dayside observations in 2005 and 2007-2009. Such difference can be explained by several possible factors: solar activity, the orbital altitude of the satellite and the local time of observations. Below we discuss the influence of these three factors in details.

1) Solar activity dependence. Figure 2 shows that we observe more events during years

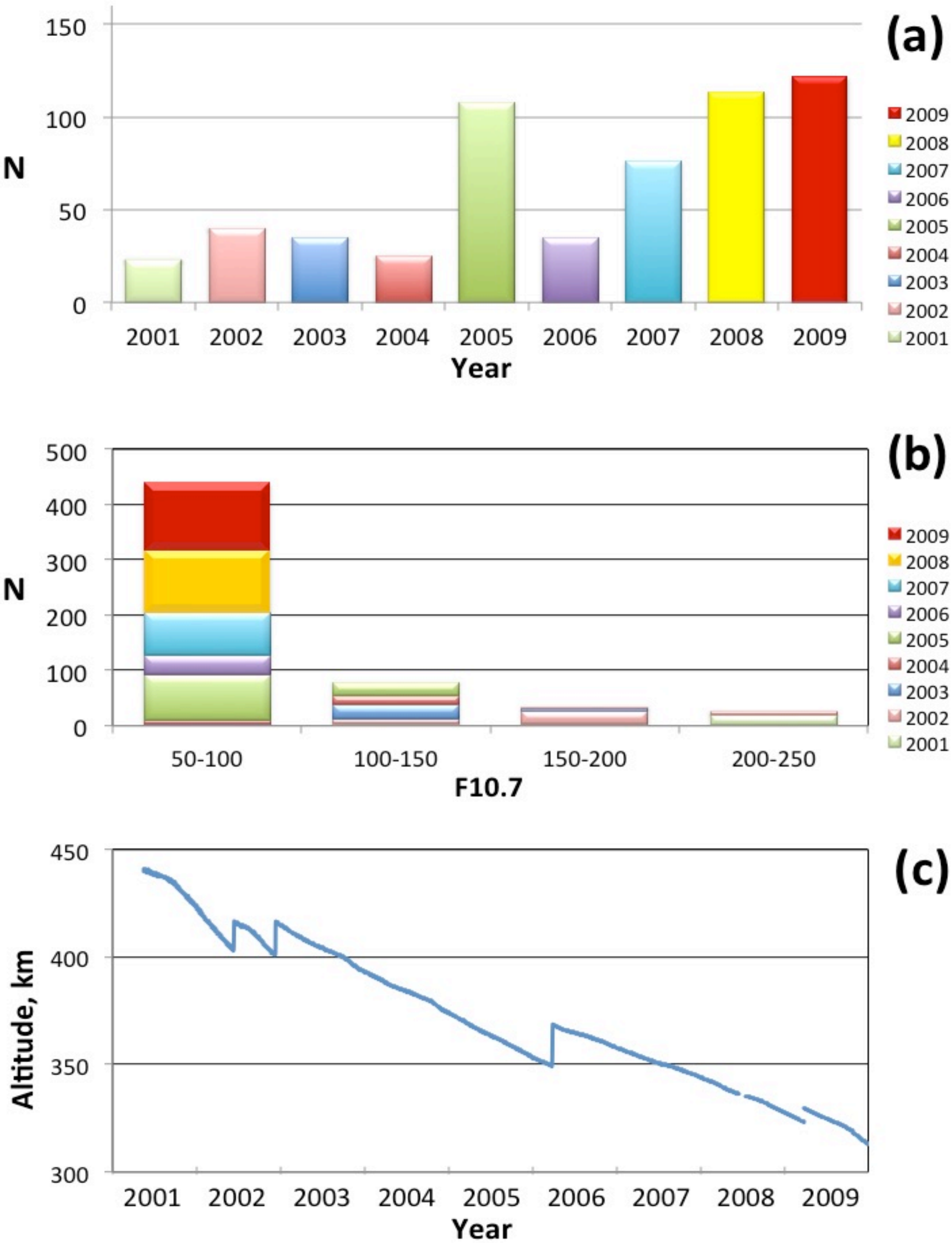

Figure 2. (a) Occurrence of the 3-peak density structures during 2001-2009 as derived from CHAMP PLP observations of the electron density. Data for each year are marked by different color as shows the legend on the right. It should be noted that for 2001, we only had data from 05 May, i.e. not the whole year data set; **(b)** – occurrence of the 3-peak structures with respect to the solar index F10.7; **(c)** – variations of the CHAMP orbital altitude during the years of the mission.

of low solar activity than during high solar activity. This feature can be seen very clearly in the dependence on the solar F10.7 index: one can see that the majority of events occur when F10.7 varies from 50 to 100 (Figure 2b). Such dependence could be explained by stronger influence of the electrodynamics on the ionosphere during high solar activity, while during low solar activity the effect of the thermospheric winds becomes significant as well. This explanation is in line with the fact that the occurrence of the 3rd ionization peak is attributed to the meridional neutral winds.

2) The orbital altitude of CHAMP changed from ~440 km in May 2001 to ~320 km in December 2009 (Figure 2c), which might have influenced our statistical results. It is known that the EIA is an F-region structure, and therefore, a satellite at lower orbital altitude is more probable to detection the 3-peak events.

Figure 3 shows a contour plot of the electron density as a function of latitude and altitude using the SAMI3 model (Huba et al., 2000; Huba and Joyce, 2010). The plot is along longitude 203° at 04:45UT on 14 May 2009. The geophysical conditions used are F10.7 = 75.5, F10.7A = 71.2, and Ap = 8. The neutral density and temperature used the NRLMSISE00 model (Picone et al., 2002) and the neutral wind used the HWM14 model (Drob et al., 2014). At this time and longitude the CHAMP satellite at ~ 330 km observed the formation of the 3-

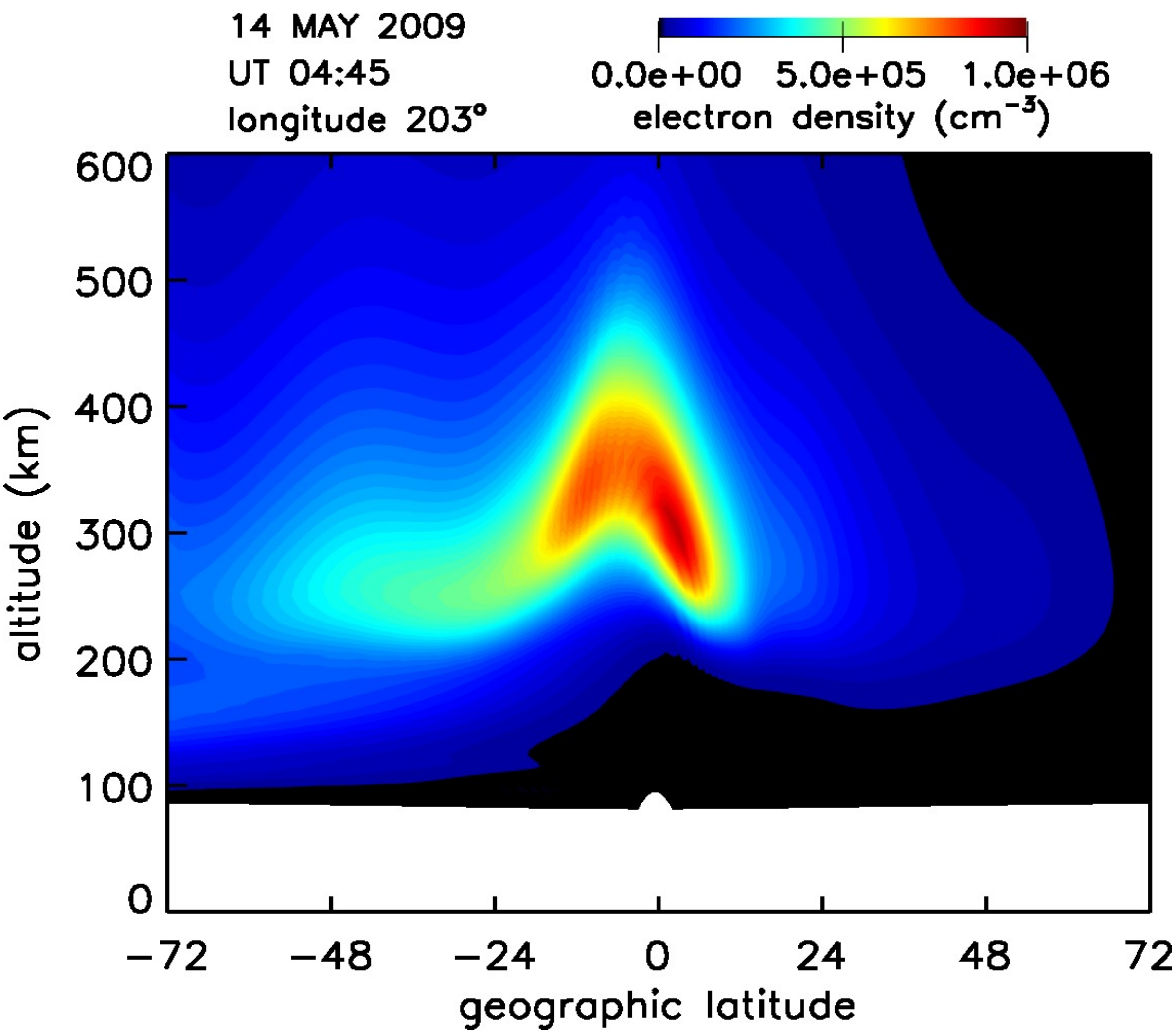

Figure 3. SAMI3-calculated electron density along 203° longitude at 4.81UT on 14 May 2009. Latitudinal density profiles at the altitudes of 300 and 330 km are shown in Figure 4.

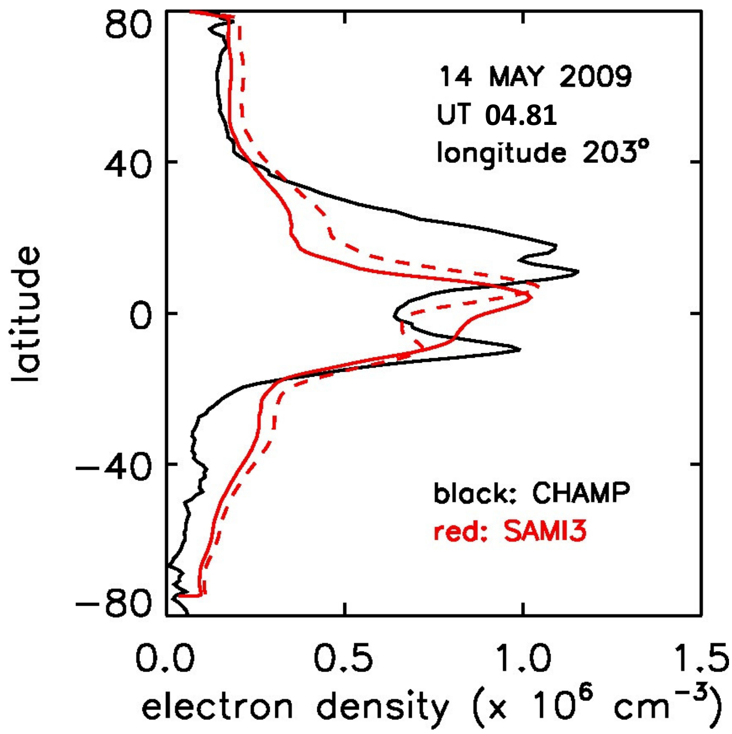

Figure 4. Latitudinal electron density profiles observed by the CHAMP satellite at the altitude of (black curves) and modelled by the SAMI3 model (red curves) at the time, longitude and altitude of the observations, as indicated on the panel. The dashed red curve is for 300 km, solid red curve is for 330 km.

peak density structure (Figure 1). However, there is no clear 3-peak structure in Figure 3; rather, the standard 2-peak Appleton anomaly is observed.

To be more quantitative we show Figure 4 which is a plot of the electron density as a function of latitude. The solid black curve is from CHAMP data at an altitude ~ 330 km, the solid red curve is from SAMI3 at the same altitude, and the dashed red curve is from SAMI3 at a lower altitude ~ 300 km. The peak SAMI3 density is comparable to the peak CHAMP density. However, at 330 km there is only a single peak in the SAMI3 results; a clear 2-peak structure is observed at the lower altitude 300 km. The location of the southern peak is consistent with the CHAMP data but not the northern peak. There is a hint of a peak in the SAMI3 results at ~ 30 degrees but it is weak.

To further study the altitudinal extent of the 3-peak events, it is interesting to analyze data from the recent ESA's constellation mission Swarm that was launched on 22 November 2013. Two of the Swarm satellites (A and C) were placed at ~440-460 km, while the third one (Swarm B) – at ~515-530 km. It should be noted that the Swarm data set from the beginning of the mission covered the maximum of the current 24^{th} solar cycle, however, in values of F10.7 index, years 2014-2015 are comparable with 2003-2004 rather than with the years 2001-2002 of the solar maximum of the previous 23^{rd} solar cycle. Therefore, in 2014-2015 the lower Swarm A satellite flew higher than CHAMP, but under similar solar conditions.

To analyze the occurrence of the 3-peak electron density structures in 2014-2015, we analyze 4 months of data from Swarm A and Swarm B satellites for the solstice periods as the time of most probable occurrence of the 3-peak events (as shown by Astafyeva et al., 2016). Our analysis of the Swarm A and Swarm B data for December 2014, January and May-June 2015 revealed that at these altitudes the 3-peak structures can occur as well (see example in Figure 5), at almost the same rate as during 2003-2004, and in SWA data they occurred more often than in SWB data. These our results demonstrate that, indeed, the 3^{rd} ionization peak is ionospheric F-region feature, but it also can be observed above 500km.

3) The local time of observations made by a satellite may play a role as well. Thus, the LT of the CHAMP equatorial crossings constantly shifted throughout the mission. As Astafyeva et al. (2016) showed, the 3–peak structures mostly occur in the local afternoon hours, which means that CHAMP may detect more events when is passes in these "favorable" sectors. However, our analysis of data from years 2001-2002 showed that very few events occur during these years, even during the local afternoon hours. The latter signifies that the

LT dependence is less important factor than that on solar activity and on a satellite orbital altitude.

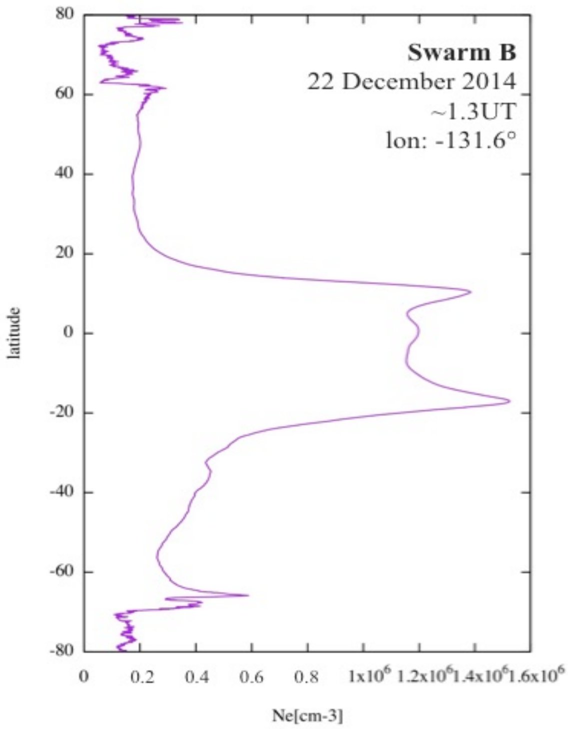

Figure 5. 3-peak Ne structure observed by Swarm B on 22 December 2014 at the altitude ~515 km.

3. CONCLUSIONS

We made analysis of the occurrence of the 3-peak density structures during the years 2001-2002 from CHAMP data in addition to 2003-2009 made previously by Astafyeva et al. (2016). Adding these years did not change the results previously reported: the 3-peak structures occur occasionally in the local afternoon hours in the summer hemisphere. Our new results also confirmed the previous results on the more probable occurrence of such kind of events during low solar activity than during high solar activity. In addition to these dependencies, here we analyzed 4 months of data from Swarm A and B satellites flying at ~460km and ~530km, respectively. The analysis of the Swarm data showed that the 3-peak density structures at these altitudes occasionally as well.

Concerning the modeling of the third ionization peak, we note that Maruyama et al. (2016) successfully modeled 3-peak structures for the December 2012 solstice conditions using the IPE model. However, the solar F10.7 index was 120 in that study. Here we used the SAMI3 to test whether it can reproduce the 3-peak events that were observed by CHAMP satellite during quiet-time conditions. The results for the 14 May 2009 simulation did not clearly show a 3-peak structure but the more traditional 2-peak structure although there was a hint of a 3rd peak. This suggests that the thermospheric conditions used in the simulation study needs to be improved to capture a 3-peak structure.

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