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## BRIEF REPORT

10.1002/2014JA020227

## Key Points:

- A new finding of electron temperature anomalies at Weddell Sea latitudes
- The eastward drift of reductions and/or enhancements in the electron density
- The electron temperature is inversely proportional to the electron density

## Correspondence to:

J. Y. Liu,  
jyliu@jupiter.ss.ncu.edu.tw

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## Topside ionospheric electron temperature and density along the Weddell Sea latitude

J. Y. Liu<sup>1,2,3</sup>, F. Y. Chang<sup>1</sup>, K. I. Oyama<sup>1</sup>, Y. Kakinami<sup>4</sup>, H. C. Yeh<sup>1</sup>, T. L. Yeh<sup>5</sup>, S. B. Jiang<sup>5</sup>, and M. Parrot<sup>6</sup>
<sup>1</sup>Institute of Space Science, National Central University, Jhongli, Taiwan, <sup>2</sup>Center for Space and Remote Sensing Research, National Central University, Jhongli, Taiwan, <sup>3</sup>National Space Program Origination, Hsin-Chu, Taiwan, <sup>4</sup>School of Systems Engineering, Kochi University of Technology, Kami, Kochi, Japan, <sup>5</sup>Department of Mechanical Engineering, National Cheng Kung University, Jhongli, Taiwan, <sup>6</sup>LPCE/CNRS, Orleans, France

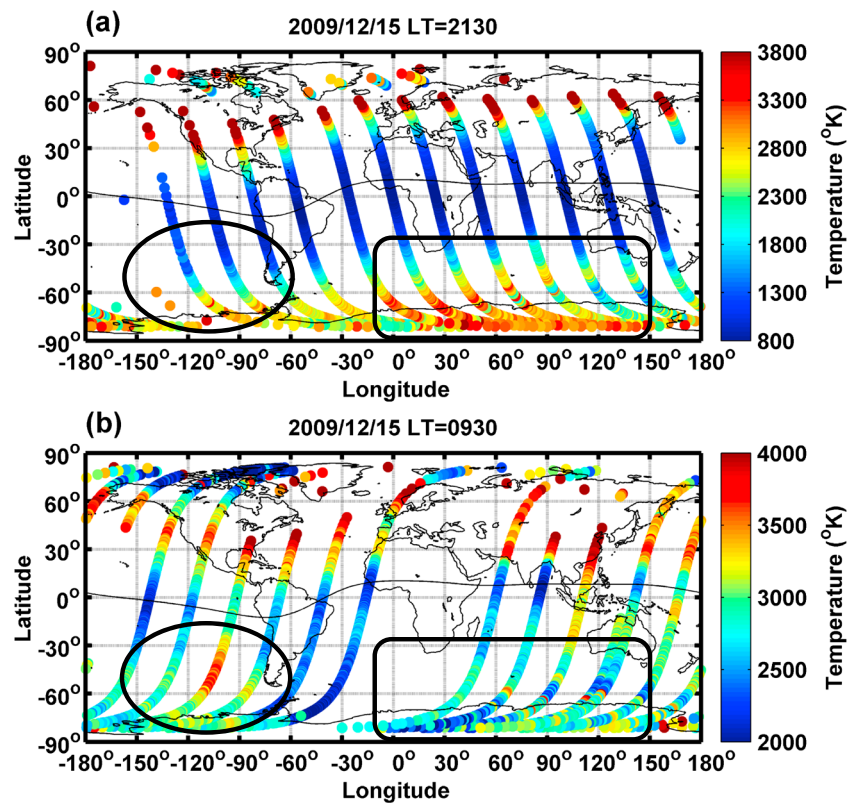
**Abstract** It has been well known that the ionospheric electron density  $N_e$  is greater in the summer nighttime than daytime around the Weddell Sea region, which is named Weddell Sea Anomaly (WSA). This paper for the first time reports unusual increases (decreases) of the daytime (nighttime) electron temperature  $T_e$  at about 830 km altitude over the WSA latitudes probed by Tatiana-2 during December 2009 to January 2010. Concurrent measurements at 660–830 km altitude observed by Tatiana-2, Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions (DEMETER), and Formosa Satellite 3/Constellation Observing System for Meteorology, Ionosphere and Climate (F3/C) reveal the anticorrelation between  $T_e$  and  $N_e$  along the WSA latitudes in the daytime and nighttime. Based on F3/C  $N_e$  along the WSA latitudes observed at various local times, the associated  $T_e$  values are computed. The Tatiana-2 and DEMETER observations as well as the computed results show that  $T_e$  yield the maximum values over the WSA region during daytime and over the Indian and Atlantic Ocean area during nighttime. The maxima or minima in F3/C  $N_e$  and the computed  $T_e$  reveal eastward phase shifts.

## 1. Introduction

Many studies report that the ionospheric electron density  $N_e$  is greater in nighttime than daytime around the Weddell Sea region around Antarctic Peninsula during the southern summer months (November, December, and January), which is termed Weddell Sea Anomaly (WSA) [Bellchambers and Piggott, 1958; Horvath and Essex, 2003; Horvath, 2006; Burns et al., 2008; He et al., 2009; Jee et al., 2009; Lin et al., 2009; Liu et al., 2010]. This peculiar behavior was first observed by ground-based ionosondes located in Antarctica back in the 1950s [Bellchambers and Piggott, 1958] and further investigated by two-dimensional maps over the oceans using total electron content measurements collected by the TOPEX/Poseidon [Horvath and Essex, 2003; Horvath, 2006; Jee et al., 2009] and three-dimensional  $N_e$  constructed by vertical profiles from 100 to 800 km altitudes of Formosa Satellite 3/Constellation Observing System for Meteorology, Ionosphere and Climate (FORMOSAT-3/COSMIC) (F3/C) [Schreiner et al., 2007; Lin et al., 2009, 2010]. Recently, Slominska et al. [2014] reported the nighttime  $N_e$  enhancements over the WSA region by Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions (DEMETER) satellite, quasi-Sun-synchronous orbit at 660 km altitude, descending/ascending nodes at 10:30/22:30 LT, with an inclination of 98.3° [Lebreton et al., 2006]. Although peculiar  $N_e$  behavior over the WSA region has been intensively studied, the associated electron temperature  $T_e$  has not yet been reported.

Tatiana-2 is an experimental scientific education microsatellite and was launched on 17 September 2009 into a circular and quasi-Sun-synchronous circular orbit at 830 km altitude averagely with an orbital inclination angle of 98.785° [Kalegaev, 2009]. The orbital period is about 100 min including ascending at 09:30 LT and descending at 21:30 LT with all longitudes within  $\pm 80^\circ$  latitude. A scientific payload, Block of Central University (BCU), developed by Taiwan was onboard Tatiana-2 [Jiang et al., 2012; Liu et al., 2012]. The electron temperature probe on Tatiana-2/BCU measures the global  $T_e$  at 09:30 and 21:30 LT.

In this study, we cross compare  $N_e$  at 700 km altitude by F3/C,  $T_e$  at 830 km altitude observed by Tatiana-2, and  $T_e/N_e$  at 660 km altitude probed by DEMETER to find the relationship between the two quantities along the WSA latitudes during the period of 15 December 2009 to 18 January 2010 (for simplicity, hereafter 2009 December solstice month).



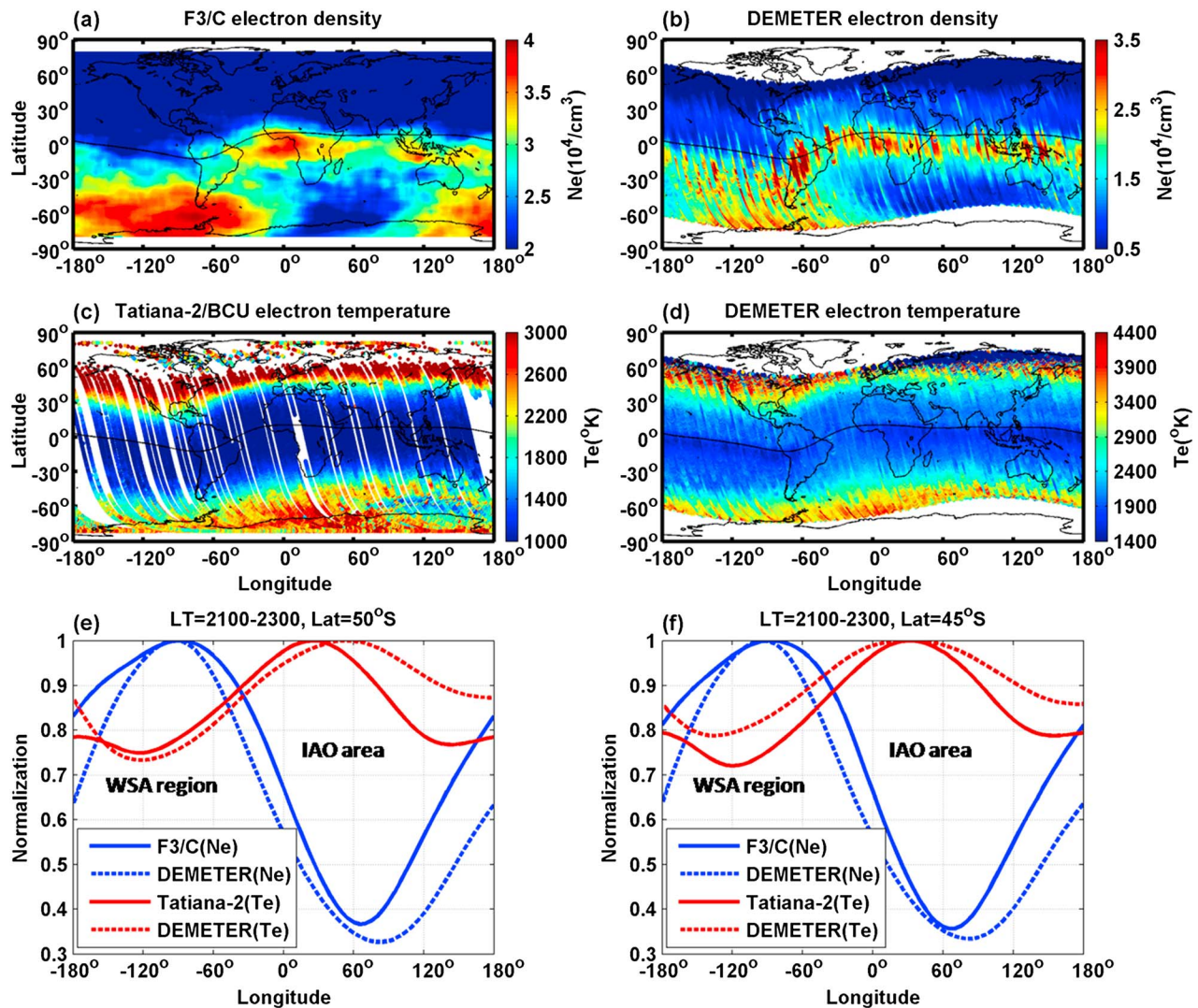
**Figure 1.** The electron temperature distributions measured by the Tatiana-2 on 15 December 2009. (a) Ascending orbit at global fixed local time 21:30 LT and (b) descending orbit at 09:30 LT. The circle and rectangle denote the WSA region and IAO area, respectively.

## 2. Observation and Cross Comparison

Since the WSA is a well-known nighttime feature, we then first examine the associated  $T_e$ . Figure 1 illustrates  $T_e$  in 1 day orbit of Tatiana-2 at 21:30 LT and 09:30 LT on 15 December 2009 (i.e., during the southern summer). It is found that  $T_e$  over the WSA region decreases in the nighttime and, however, remarkably increases in the daytime. By contrast,  $T_e$  over the Indian and Atlantic Oceans, which is termed the Indian and Atlantic Ocean (IAO) area, increases in the nighttime but decreases in the daytime.

The F3/C  $N_e$  being subgrouped into 09:00–11:00 LT and 21:00–23:00 LT together with Tatiana-2  $T_e$  at 09:30 and 21:30 LT are cross compared with DEMETER  $N_e$  and  $T_e$  at 10:30 and 22:30 LT, respectively. Figure 2 displays  $N_e$  of F3/C and DEMETER as well as  $T_e$  of Tatiana-2 and DEMETER during the nighttime of the 2009 December solstice month. As expected,  $N_e$  probed by F3/C and DEMETER unusually increase centering at the WSA region and expanding over a large area between 30°S to 80°S and 30°W to 180°W (Figures 2a and 2b). It can be seen that the associated  $T_e$  observed by Tatiana-2 and DEMETER decreases (Figures 2c and 2d). By contrast,  $T_e$  increases associated with  $N_e$  reductions appear over the IAO area, 30°S to 80°S and 0°E to 105°E (Figures 2a–2d). To further examine the relationship between  $T_e$  and  $N_e$  in detail, the data in Figures 2a–2d along 50°S geographic (near the center latitude of the WSA region and the IAO area) and 45°S geographic (avoiding/minimizing the auroral effect) are extracted. Figures 2e and 2f display that the data along the 50°S and 45°S latitudes being nearly identical and that the two  $T_e$  tend to reach their minima (maxima) when the associated  $N_e$  yield the maxima (minima) over the WSA region (IAO area) during the nighttime.

Figure 3 illustrates the daytime observations that  $N_e$  by F3/C and DEMETER reduce (Figures 3a and 3b), and the associated  $T_e$  by Tatiana-2 and DEMETER prominently increase around the WSA region, 20°S–70°S and 60°W–180°W (Figures 3c and 3d). In contrast, when the two  $N_e$  enhance, the associated  $T_e$  decrease accordingly over the IAO area. Again, Figures 3e and 3f reveal that the data along the 50°S and 45°S latitudes are very similar and that when the two  $N_e$  approach the minima (maxima) over the WSA region (IAO area), the



**Figure 2.** The electron density and electron temperature distributions measured by the F3/C, DEMETER, and Tatiana-2 during global nighttimes of the December month in 2009. (a) F3/C electron density at 22:00 LT, (b) DEMETER electron density at 22:30 LT, (c) Tatiana-2 electron temperature at 21:30 LT, (d) DEMETER electron temperature at 22:30 LT, (e)  $T_e$  and  $N_e$  extracted along the 50°S geographic, and (f) along the 45°S geographic.

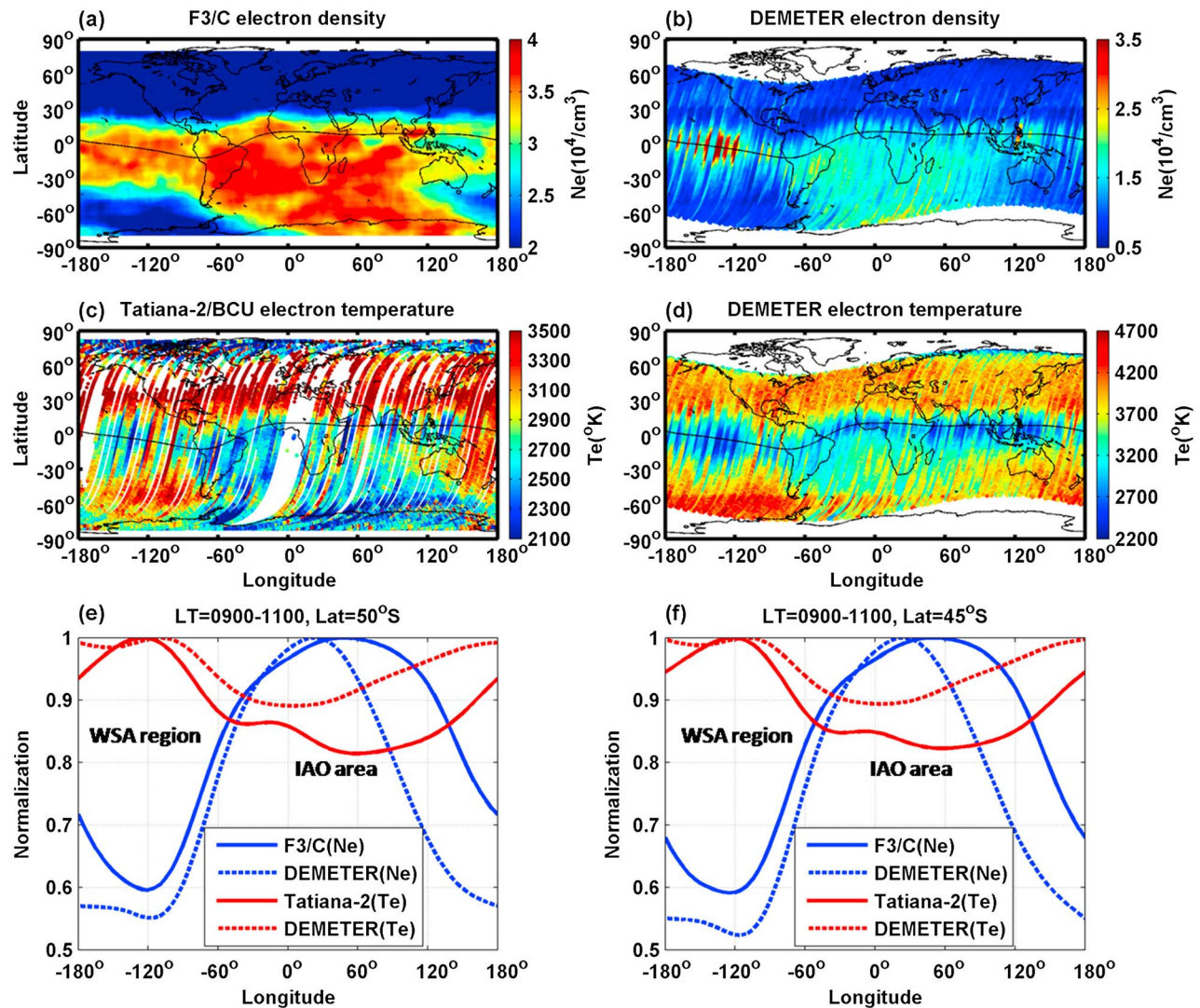
associated  $T_e$  tend to reach their maxima (minima) during the daytime. Figures 2 and 3 suggest the existence of the anticorrelation between  $T_e$  and  $N_e$  at the WSA latitudes in both nighttime and daytime. That is  $N_e$  reduction (enhancement) resulting in  $T_e$  increase (decrease).

### 3. Discussion

It has been known that  $T_e$  is governed by heating of photoelectron and cooling caused by Coulomb collisions among ions and neutral species in the ionosphere [cf., Schunk and Nagy, 1978; Watanabe *et al.*, 1995; Kakinami *et al.*, 2011]. The elevation angle at 600 km altitude is about  $-24^\circ$ , and therefore, the ionosphere beyond  $42.5^\circ\text{S}$  probed by Tatiana-2 and/or DEMETER is almost always under a quasi 24 h daylight condition in the December solstice month. Thus, the heating of the photoelectron at above 600 km altitude of the middle- and high-latitude ionosphere in the southern hemisphere can approximately be a constant. By contrast, above 200 km altitude, the  $T_e$  cooling rate is inversely proportional to the square of  $N_e$  [Schunk and Nagy, 1978].

On the other hand, plasmaspheric heating could be important in high latitudes at night. To study and confirm the anticorrelation along the WSA latitudes, we examine  $T_e$  versus  $N_e$  at  $45^\circ$  and  $50^\circ$ . Note that auroral effects

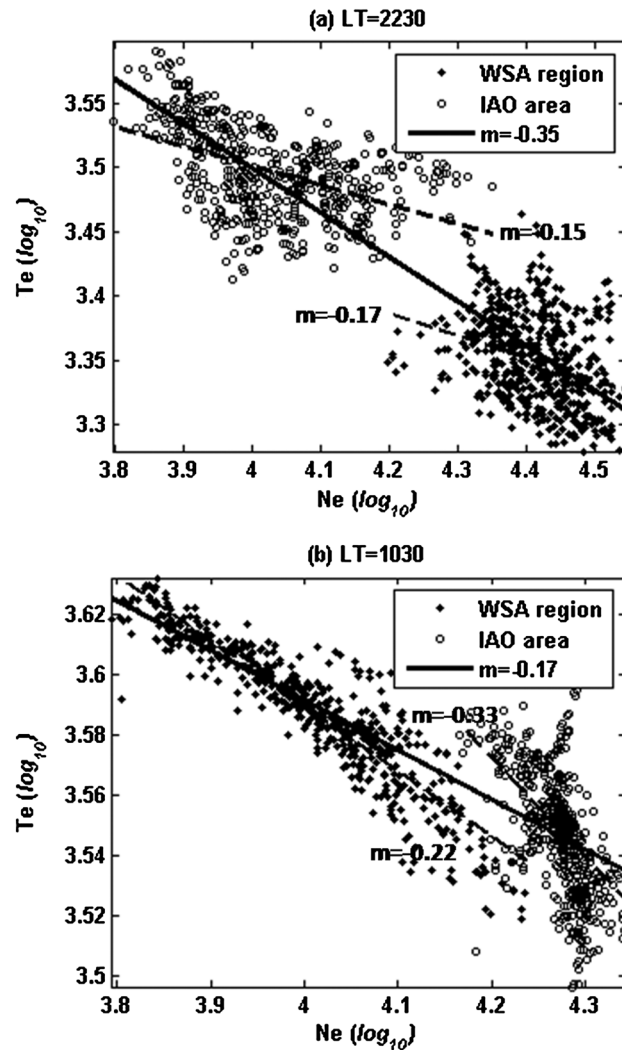




**Figure 3.** The electron temperature and electron density distributions measured by the F3/C, DEMETER, and Tatiana-2 during global daytimes of the 2009 December solstice month. (a) F3/C electron density at 10:00 LT, (b) DEMETER electron density at 10:30 LT, (c) Tatiana-2 electron temperature at 09:30 LT, (d) DEMETER electron temperature at 10:30 LT, (e)  $T_e$  and  $N_e$  extracted along the 50°S geographic, and (f) along the 45°S geographic.

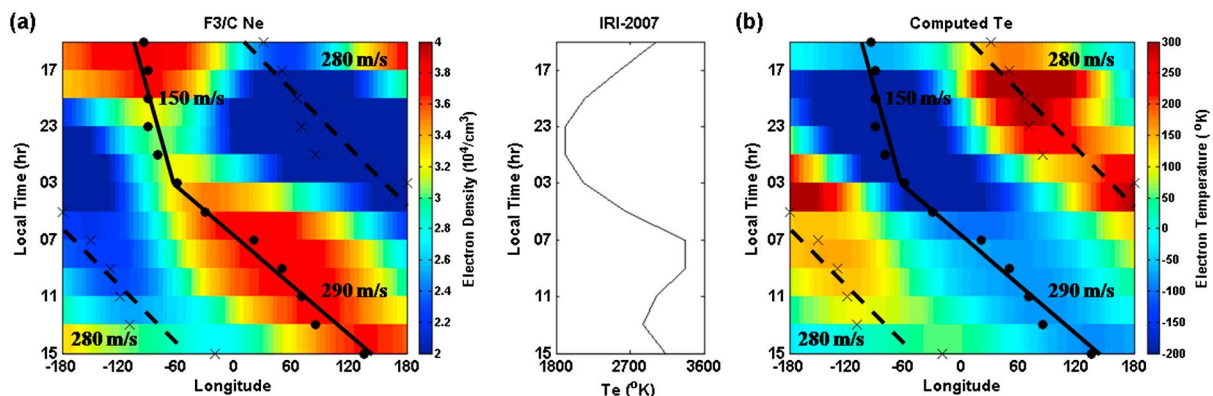
mainly occur at 65° magnetic latitude and greater and that the chance of observing auroras is less 5% (<http://www.skyandtelescope.com/observing/an-aurora-watchers-guide/#sthash.gnc2Zo4B.dpuf>); the auroral heating effect in the temperature at 45° latitude should be insignificant. In fact, DEMETER stops its observations over the auroral region (65°S geomagnetic) [Lebreton *et al.*, 2006; Kakinami *et al.*, 2011]. Nevertheless, the nearly identical variations in Figures 2e (3e) and 2f (3f) strongly suggest that the anticorrelation is unlikely related to the effect of the auroral heating on the high-latitude temperature during the nighttime.

To validate the anticorrelation, we extract and examine the  $T_e$  and  $N_e$  along 45°S concurrently/collocatedly observed by DEMETER in the WSA region and IAO area during the daytime and nighttime shown in Figures 2 and 3. Negative values of the slopes over the two (WSA and IAO) regions during both nighttime (−0.15 and −0.17) and daytime (−0.33 and −0.22) as well as the overall nighttime (−0.35) and overall daytime (−0.17) suggest the anticorrelation at WSA latitude during the December solstice month (see Figure 4). We further apply Loftus and Loftus [1988] to find the confidence of the above anticorrelation. The correlation coefficient (confidence interval 95%) −0.3282 (−0.25 and −0.4), −0.4687 (−0.4 and −0.53), −0.892 (−0.879 and −0.903), −0.916 (−0.9 and 0.93), −0.4687 (−0.4 and −0.53), and −0.838 (−0.82 and −0.855) of the WSA region, IAO area, and overall during the nighttime (daytime) confirm the existence of the anticorrelation between  $T_e$  and  $N_e$ .



**Figure 4.** The anticorrelation between  $N_e$  and  $T_e$  by using DEMETER near the center of the WSA region and IAO area during the daytime and nighttime. (a) 22:30 LT and (b) 10:30 LT. The dots and circles denote the observations over the WSA region and IAO area, respectively. The solid and dashed lines are the slopes of overall and the two regions.

Figures 2e and 2f and Figures 3e and 3f reveal that the maximum (minimum) of  $T_e$  is shifted from the minimum (maximum) of  $N_e$  by about  $30^\circ$  in longitude during the nighttime and  $10^\circ$  during the daytime, respectively. Note that  $T_e$  mainly results from local solar heating and Coulomb cooling, while  $N_e$  is significantly affected by neutral winds. Kakinami *et al.* [2011] observed that the locations of the longitudinal structures of  $N_e$  and  $T_e$  do not perfectly match (i.e., shift) each other. They explain that the shift could be caused not only by zonal wind driven by dynamo effects, especially those the modulated electric field by nonmigrating tides, but also by meridional winds which may modify the longitudinal structures of  $N_e$  in the topside ionosphere. Meanwhile, Figure 4 displays that the slopes in WSA region and IAO area are different in nighttime or daytime, which suggests that the anticorrelation has longitudinal effects. Thus, the longitudinal effects on the anticorrelation could also result in the shift between the maximum (minimum) of  $T_e$  and the minimum (maximum) of  $N_e$ . Moreover, the shift being larger during the nighttime than the daytime that is similar to the shift between  $N_e$  and effective neutral wind [Chang *et al.*, 2012]. Therefore, it might be that the stronger meridional and/or zonal winds, which in turn modify the dynamo, enlarge the shift in the nighttime. Nevertheless, the shift between  $T_e$  and  $N_e$  is rather complex, which is worth to be investigated in the future.



**Figure 5.** Diurnal variations of the F3/C  $N_e$  at 700 km altitude and computed  $T_e$  along  $45^\circ\text{S}$  during the 2009 December solstice month. (a) F3/C  $N_e$  and (b) computed offset  $T_e$ . The background  $T_e$  is computed by International Reference Ionosphere 2007 which is given between Figures 5a and 5b. The dots and cross symbols denote the  $N_e$  maxima and  $T_e$  minima and  $N_e$  minima and  $T_e$  maxima, respectively.

Figure 5a depicts the F3/C  $N_e$  at 700 km altitude along 45°S (the WSA latitude) at various local times. Based on the slopes of anticorrelation shown in Figure 4 and  $N_e$  in Figure 5a, we compute the associated offset  $T_e$  (Figure 5b). Figure 5 reveals that the F3/C  $N_e$  enhancement or computed  $T_e$  decrease exhibits dual eastward phase shifts of about 150 and 290 m/s during 17:00–03:00 LT (150°W to 60°W) and 03:00–17:00 LT (60°W to 170°E), respectively. By contrast, the  $N_e$  reduction or  $T_e$  increase yields sole eastward phase shift at approximately 280 m/s. Figure 5b depicts that the computed  $T_e$  yields the greatest value over the WSA region during daytime, which agrees with  $T_e$  observed by Tatiana-2 (Figure 3c).

#### 4. Summary and Conclusion

It is well known that  $N_e$  is greater in nighttime than daytime over the WSA region during the southern summer months. Measurements of F3/C, Tatiana-2, and DEMETER are employed to find how  $T_e$  responses to this peculiar  $N_e$  behavior along the WSA latitudes during the December solstice month of 2009. Under a quasi 24 h daylight condition, the heating of the photoelectron in the middle- and high-latitude ionosphere in the southern hemisphere is approximately constant during the December solstice month. Vice versus the Coulomb cooling might play an important role. The correlation coefficient with confidence interval 95% proves the existence of the anticorrelation between  $T_e$  and  $N_e$  due to the Coulomb cooling. Based on the anticorrelation and the F3/C  $N_e$  observations,  $T_e$  would reveal eastward phase shifts. In conclusion, this paper for the first time reports that unusual  $T_e$  increase features are associated with  $N_e$  reduction appearing over the WSA region during the daytime and the IAO area during the nighttime in the December solstice month of 2009. The anticorrelation between  $N_e$  and  $T_e$  can be used to explain the appearance of the  $T_e$  unusual increase.

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