Topside ionospheric electron temperature and density along the Weddell Sea latitude

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AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

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

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Citation:
Liu, J. Y., F. Y. Chang, K. I. Oyama, Y. Kakinami, H. C. Yeh, T. L. Yeh, S. B. Jiang, and M. Parrot (2015), Topside ionospheric electron temperature and density along the Weddell Sea latitude, *J. Geophys. Res. Space Physics*, *120*, 609–614, doi:10.1002/2014JA020227.

Received 28 MAY 2014
Accepted 22 NOV 2014
Accepted article online 26 NOV 2014
Published online 6 JAN 2015

Topside ionospheric electron temperature and density along the Weddell Sea latitude

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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 ±80° 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).

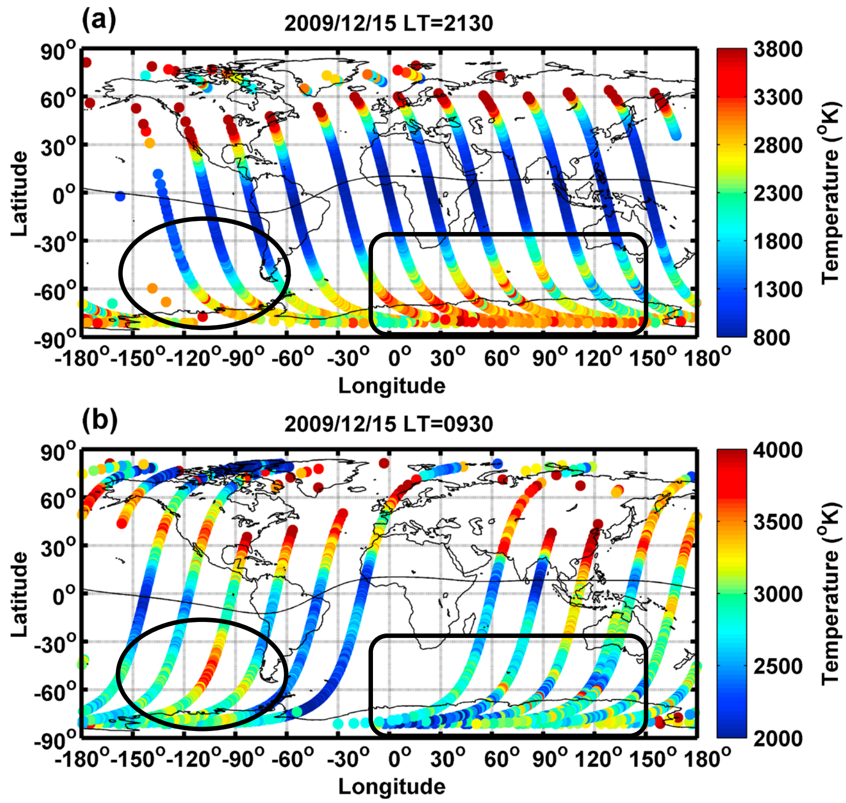

Figure 1. The electron temperature distributions measured by the Tatiana-2 on 15 December 2009. (a) Ascending orbit at global fixed local time 21:30 LT and (b) descending orbit at 09:30 LT. The circle and rectangle denote the WSA region and IAO area, respectively.

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

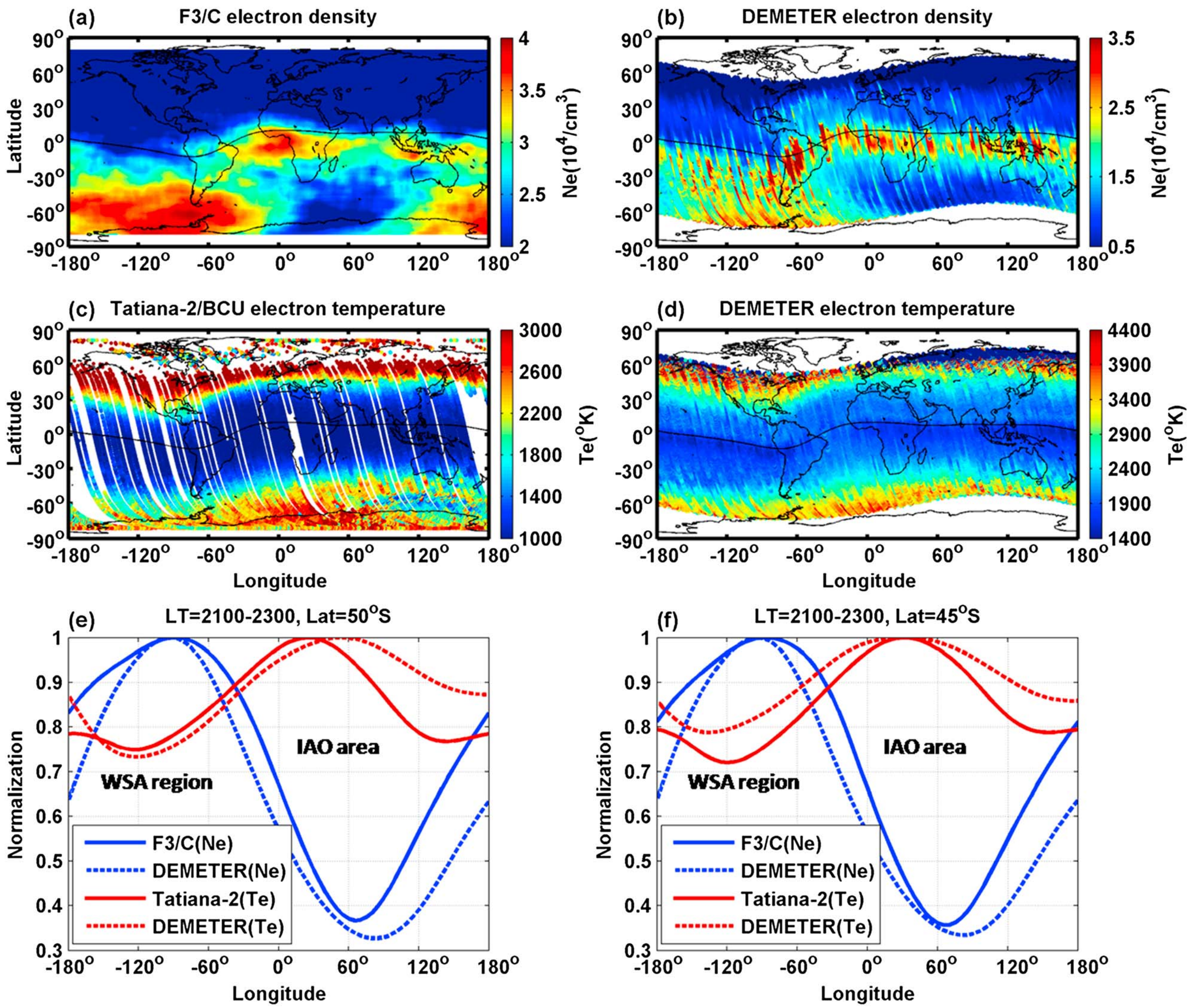

Figure 2. The electron density and electron temperature distributions measured by the F3/C, DEMETER, and Tatiana-2 during global nighttimes of the December month in 2009. (a) F3/C electron density at 22:00 LT, (b) DEMETER electron density at 22:30 LT, (c) Tatiana-2 electron temperature at 21:30 LT, (d) 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°, and therefore, the ionosphere beyond 42.5°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° and 50°. Note that auroral effects

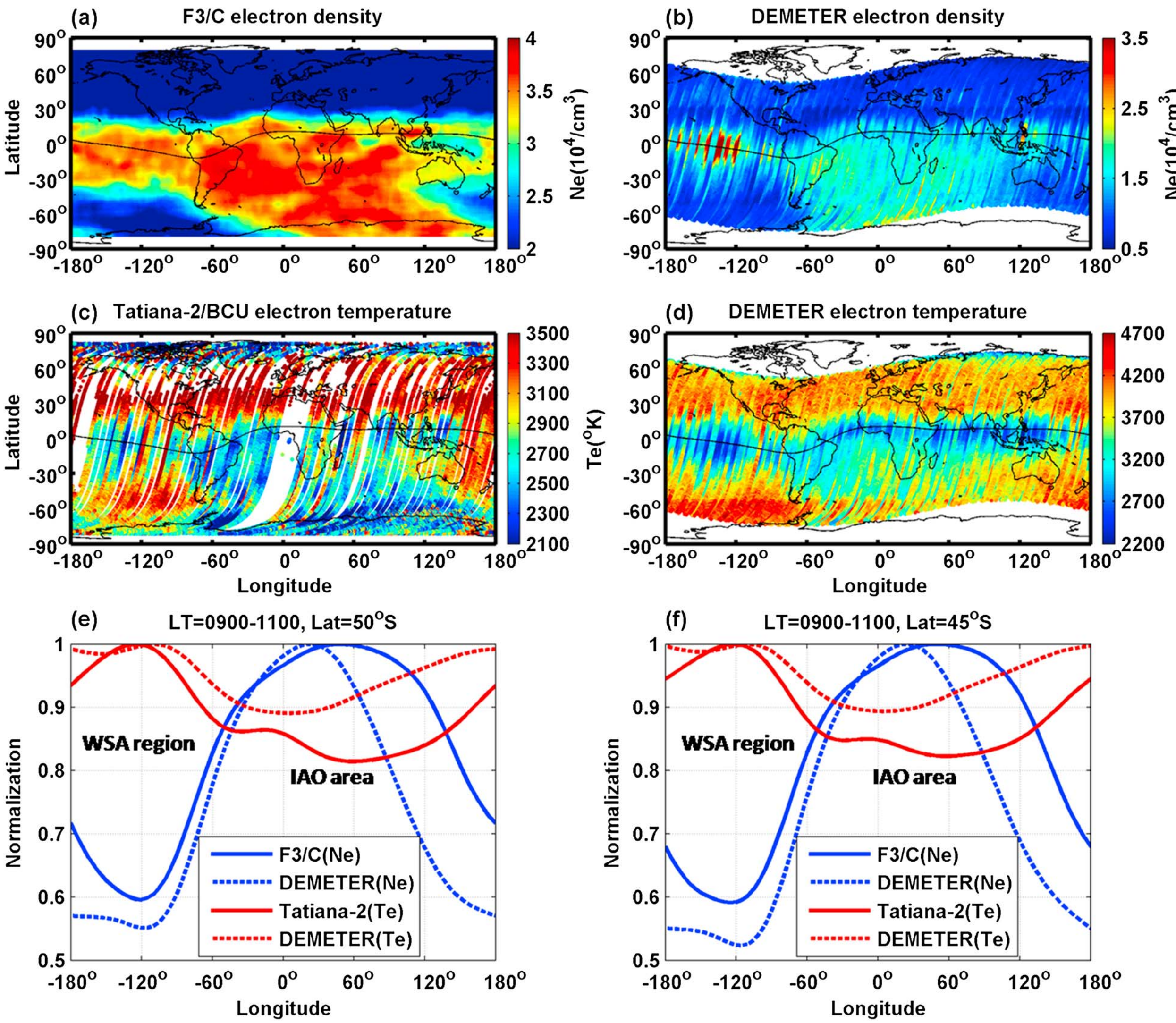

Figure 3. The electron temperature and electron density distributions measured by the F3/C, DEMETER, and Tatiana-2 during global daytimes of the 2009 December solstice month. (a) F3/C electron density at 10:00 LT, (b) DEMETER electron density at 10:30 LT, (c) Tatiana-2 electron temperature at 09:30 LT, (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.

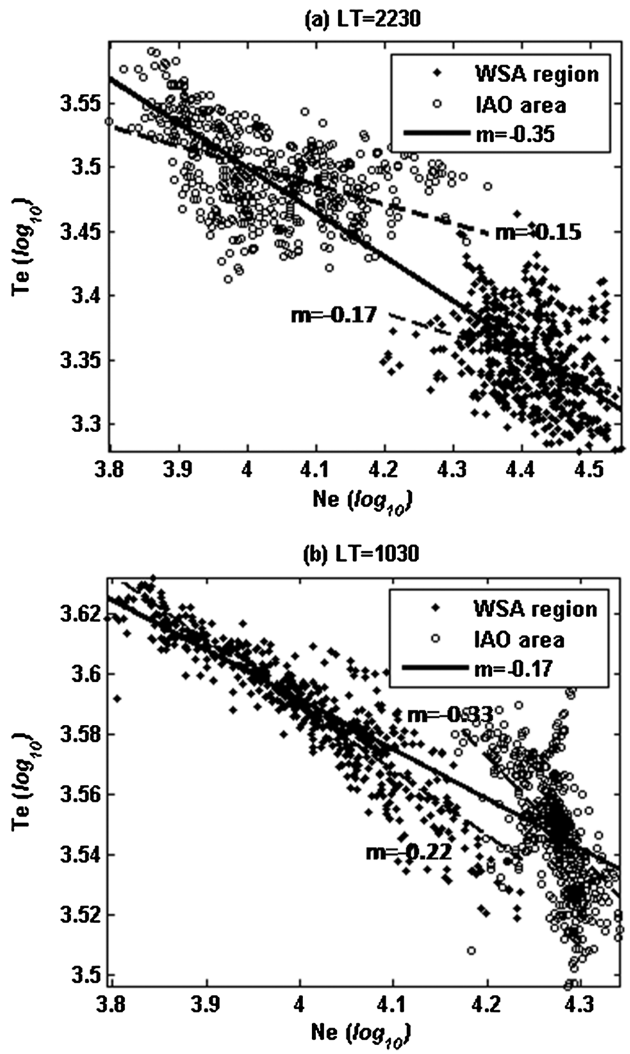

Figure 4. The anticorrelation between N_e and T_e by using DEMETER near the center of the WSA region and IAO area during the daytime and nighttime. (a) 22:30 LT and (b) 10:30 LT. The dots and circles denote the observations over the WSA region and IAO area, respectively. The solid and dashed lines are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

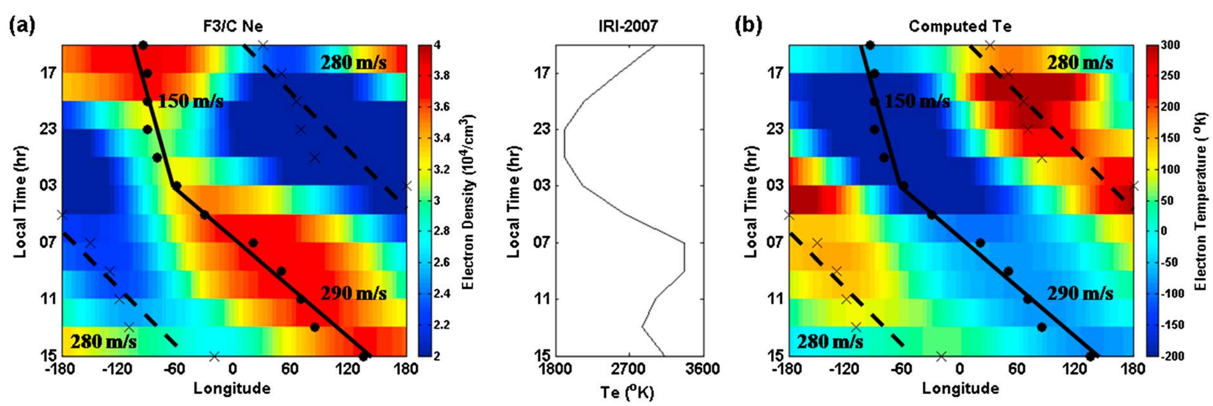

Figure 5. Diurnal variations of the F3/C N_e at 700 km altitude and computed T_e along 45°S during the 2009 December solstice month. (a) F3/C N_e and (b) computed offset T_e. The background T_e is computed by International Reference Ionosphere 2007 which is given between Figures 5a and 5b. The dots and 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.

Acknowledgments

This research work is partially supported by the National Space Organization grant (Taiwan-Russia Satellite Project) 97-NSPO(B)-SE-FA07-02 and the Ministry of Science and Technology 103-2628-M-008-001. Tatiana-2 data can be obtained from S.B. Jiang at the National Central University (t330008@cc.ncu.edu.tw). FORMOSAT-3/COSMIC data are available at Taiwan Analysis Center for COSMIC (http://tacc.cwb.gov.tw/) and/or COSMIC Data Analysis and Archival Center (http://cdaac-www.cosmic.ucar.edu/cdaac/), while DEMETER data can be retrieved from http://demeter.cnrs-orleans.fr/.

Michael Liemohn thanks the reviewers for their assistance in evaluating this paper.

References

Bellchambers, W. H., and W. R. Piggott (1958), Ionospheric measurements made at Halley Bay, *Nature*, *188*, 1596–1597.

Burns, A. G., Z. Zeng, W. Wang, J. Lei, S. C. Solomon, A. D. Richmond, T. L. Killeen, and Y. H. Kuo (2008), Behavior of the F2 peak ionosphere over the South Pacific at dusk during quiet summer conditions from COSMIC data, *J. Geophys. Res.*, *113*, A12305, doi:10.1029/2008JA013308.

Chang, F. Y., J. Y. Liu, C. H. Lin, and C. H. Chen (2012), Neutral wind effect on mid latitude summer nighttime anomaly, Abstract #SA31B-2146 presented at 2012 AGU Fall Meeting, San Francisco, Calif., 3–7 Dec.

He, M., L. Liu, W. Wan, B. Ning, B. Zhao, J. Wen, X. Yue, and H. Le (2009), A study of the Weddell Sea Anomaly observed by FORMOSAT-3/COSMIC, *J. Geophys. Res.*, *114*, A12309, doi:10.1029/2009JA014175.

Horvath, I. (2006), A total electron content space weather study of the nighttime Weddell Sea Anomaly of 1996/1997 southern summer with TOPEX/Poseidon radar altimetry, *J. Geophys. Res.*, *111*, A12317, doi:10.1029/2006JA011679.

Horvath, I., and E. A. Essex (2003), The Weddell sea anomaly observed with the Topex satellite data, *J. Atmos. Sol. Terr. Phys.*, *65*, 693–706.

Jee, G., A. G. Burns, Y. H. Kim, and W. Wang (2009), Seasonal and solar activity variations of the Weddell Sea Anomaly observed in the TOPEX total electron content measurements, *J. Geophys. Res.*, *114*, A04307, doi:10.1029/2008JA013801.

Jiang, S. B., T. L. Yeh, H. C. Yeh, J. Y. Liu, Y. H. Hsu, and L. Y. Liu (2012), System architecture of the BCU payload on Tatiana-2, *Terr. Atmos. Ocean. Sci.*, *23*, 193–208, doi:10.3319/TAO.2011.09.20.01(AA).

Kakinami, Y., C. H. Lin, J. Y. Liu, M. Kamogawa, S. Watanabe, and M. Parrot (2011), Daytime longitudinal structures of electron density and temperature in the topside ionosphere observed by the Hinotori and DEMETER satellites, *J. Geophys. Res.*, *116*, A05316, doi:10.1029/2010JA015632.

Kalegaev, V. (2009), *Tatiana-2, Space Monitoring Data Center Skobeltsyn Institute of Nuclear Physics*, Moscow State Univ., Russia. [Available at http://smdc.sinp.msu.ru/index.py?nav=tat2.]

Lebreton, J. P., et al. (2006), The ISL Langmuir probe experiment processing onboard DEMETER: Scientific objectives, description and first results, *Planet. Space Sci.*, *54*, 472–486, doi:10.1016/j.pss.2005.10.017.

Lin, C. H., J. Y. Liu, C. Z. Cheng, C. H. Chen, C. H. Liu, W. Wang, A. G. Burns, and J. Lei (2009), Three dimensional ionospheric electron density structure of the Weddell Sea Anomaly, *J. Geophys. Res.*, *114*, A02312, doi:10.1029/2008JA013455.

Lin, C. H., C. H. Liu, J. Y. Liu, C. H. Chen, A. G. Burns, and W. Wang (2010), Mid latitude summer nighttime anomaly of the ionospheric electron density observed by FORMOSAT-3/COSMIC, *J. Geophys. Res.*, *115*, A03308, doi:10.1029/2009JA014084.

Liu, H., S. V. Thampi, and M. Yamamoto (2010), Phase reversal of the diurnal cycle in the midlatitude ionosphere, *J. Geophys. Res.*, *115*, A01305, doi:10.1029/2009JA014689.

Liu, L. Y., S. B. Jiang, T. L. Yeh, H. C. Yeh, J. Y. Liu, Y. H. Hsu, and J. Y. Peng (2012), The magneto-resistive magnetometer of BCU on the Tatiana-2 satellite, *Terr. Atmos. Ocean. Sci.*, *23*, 317–326, doi:10.3319/TAO.2011.11.07.01(AA).

Loftus, G. R., and E. F. Loftus (1988), Essence of statistics, 2nd ed, pp. 411–429, McGraw Hill, New York.

Schreiner, W., C. Rocken, S. Sokolovskiy, S. Syndergaard, and D. Hunt (2007), Estimates of the precision of GPS radio occultations from the FORMOSAT-3/COSMIC mission, *Geophys. Res. Lett.*, *34*, L04808, doi:10.1029/2006GL027557.

Schunk, R. W., and A. F. Nagy (1978), Electron temperatures in the F region ionosphere: Theory and observations, *Rev. Geophys.*, *16*, 355–399.

Slominska, E., J. Blecki, J.-P. Lebreton, M. Parrot, and J. Slominski (2014), Seasonal trends of nighttime plasma density enhancements in the topside ionosphere, *J. Geophys. Res. Space Physics*, *119*, 6902–6912, doi:10.1002/2014JA020181.

Watanabe, S., K. I. Oyama, and M. A. Abdu (1995), Computer simulation of electron and ion densities and temperatures in the equatorial F region and comparisonwithHinotori results, *J. Geophys. Res.*, *100*, 14,581–14,590, doi:10.1029/95JA01356.