Plausible effect of atmospheric tides on the equatorial ionosphere observed by the FORMOSAT-3/COSMIC: Three-dimensional electron density structures


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[1] The plausible effect of atmospheric tides on the longitudinal structure of the equatorial ionosphere is observed by the FORMOSAT-3/COSMIC (F3/C) constellation during September Equinox, 2006, near solar minimum. The longitudinal structure was first reported in IMAGE satellite airglow observations at the far-ultraviolet (FUV) 135.6-nm wavelength during March Equinox, 2002, near solar maximum. The global three-dimensional ionospheric electron density observed by F3/C shows a prominent four-peaked wave-like longitudinal enhancement in the equatorial ionization anomaly (EIA). The vertical electron density structures observed by F3/C reveal that the feature exists mainly above 250 km altitude indicating that the feature is an F-region phenomenon. The four longitudinal F-region enhancements of the EIA peaks may result from a stronger equatorial plasma fountain at each longitude region produced by a stronger F-region eastward electric field transmitted along the magnetic field lines from E-region where longitudinal variations in atmospheric tides affect the ionospheric dynamo process. Citation: Lin, C. H., W. Wang, M. E. Hagan, C. C. Hsiao, T. J. Immel, M. L. Hsu, J. Y. Liu, L. J. Paxton, T. W. Fang, and C. H. Liu (2007), Plausible effect of atmospheric tides on the equatorial ionosphere observed by the FORMOSAT-3/COSMIC: Three-dimensional electron density structures, Geophys. Res. Lett., 34, L11112, doi:10.1029/2007GL029265.

1. Introduction

[2] Recent studies of the longitudinal four-peaked/wavenumber-four structure of the equatorial electrojet (EEJ), and the equatorial ionization anomaly (EIA) (EIA descriptions can be found by Namba and Maeda [1939], Appleton [1946], Hanson and Moffett [1966], Anderson [1973], Balan and Bailey [1995], and Rishbeth [2000]) stimulate great interest in studying the physical mechanism responsible for the observed longitudinal structure [Vladimer et al., 1999; JadHAV et al., 2002; Lühr et al., 2004; Sagawa et al., 2005; Henderson et al., 2005; Immel et al., 2006; England et al., 2006a, 2006b]. The most surprising result of the studies is the coincidence of these structures with the locations of four nonmigrating tidal maxima and the ionospheric nightglow brightness observed by the IMAGE satellite at far-ultraviolet (FUV) 135.6 nm emission line. The observations strongly suggest that the equatorial ionosphere is coupled with a nonmigrating tide which is excited in the troposphere, possibly produced by the latent heat release in tropical cloud formation [e.g., Hagan and Forbes, 2002, 2003], propagating upward and subsequently affects the E-region dynamo electric field [Sagawa et al., 2005; Immel et al., 2006].

[3] Altitudinal observations of the electron density are important indicators of the altitude range where the proposed ionospheric dynamo electric field is operating and represent the next logical diagnostic to further explore the plausible effect of this nonmigrating tide on EIA longitude enhancements. Both IMAGE-FUV ionospheric nightglow observations [Sagawa et al., 2005; Immel et al., 2006] and total electron content (TEC) from combined ground-based GPS receiver and oceanic altimeter (e.g., TOPEX satellite [Vladimer et al., 1999]) measurements provide only a two-dimensional perspective. With the aid of satellites performing GPS radio occultation observations, three-dimensional ionospheric observations can be achieved. The FORMOSAT-3/COSMIC (F3/C) constellation, therefore, is the ideal suite of instruments to monitor vertical electron density of the wavenumber-four longitudinal structures and to further understanding of the possible coupling process between the equatorial ionosphere and the nonmigrating tides of tropospheric origin, or other possible mechanisms. It is worthwhile to note that the airglow observations by IMAGE-FUV depend on the layer thickness, absorption, and volume emission rate, while F3/C directly observes variations in electron density.

2. FORMOSAT-3/COSMIC Observation

[4] Six micro-satellites termed FORMOSAT-3/COSMIC (F3/C) were successfully launched into a circular low Earth orbit at 0140 UTC on 15 April 2006. Each satellite houses a GPS occultation experiment (GOX) payload deriving the vertical profile of electron density in the ionosphere globally [Cheng et al., 2006]. For the first time, this suite of instruments provides global instantaneous electron density profiles of both the lower and upper ionosphere extending into the altitude of the six-satellite constellation. The initial F3/C satellite orbits are close and at an altitude of 512 km, and
72° inclination angle. After 16 months the constellation will reach the mission orbit of ~800 km altitude, 72° inclination angle, and 30° separation in longitude between each satellite. Currently (as of 27 October 2006), one F3/C satellite has reached its 800 km mission altitude, separating in longitude from the other five satellites that are still clustered close together in a similar orbital plane. Although the constellation has not yet reached its final mission orbit, ~2500 ionospheric soundings are performed daily providing measurements of global three-dimensional ionospheric electron density structure up to 500 (800) km altitude. Monthly averaged global ionospheric soundings that vary with altitude can be obtained by binning measurements from 30 geomagnetically quiescent days (e.g., 15 days prior and 15 days after September 21) in two hour bins and taking median value of the soundings located in the same 5 degree by 5 degree grid in both longitude and latitude. Figures 1a and 1b show the constructed electron content map for measurements made between 2000–2200 LT and integrated from 100–500 km and 300–350 km altitudes, respectively. The integrated ionospheric electron contents between 100–500 km and 300–350 km, hereafter referred to as IEC(100–500) and IEC(300–350), respectively show a clear four-peaked longitudinal structure with large electron content occurring in the South America, Africa, Southeast Asia, and the central Pacific sectors as reminiscent of the IMAGE nightglow images. These same structures are also observed in F3/C daytime electron content measurements and will be the subject of a follow-on report.

3. Comparison With the TIMED-GUVI Observation

[5] To examine whether the four-peaked longitudinal signature also exists in the ionospheric nightglow during the same time period, 135.6 nm nightglow observation from the Global Ultraviolet Imager (GUVI) [Christensen et al., 2003] on board the NASA TIMED (Thermosphere Ionosphere Mesosphere Energy and Dynamics) satellite is presented in Figure 2. The GUVI 135.6 nm observations at 2000–2200 LT during the 15-day period after September 21, 2006 are analyzed to reconstruct the Figure 2 with similar data binning method used to create Figure 1. Four strong airglow brightness zones are clearly seen at the low-latitude longitude regions that are highly correlated with the F3/C electron density measurements. The locations of the EIA...
peaks observed by GUVI are around ±15° magnetic latitude, which is again similar to those observed by F3/C at around 300–350 km altitude (Figure 1b). The hemispheric asymmetry of the north and south EIA peaks is also seen in the GUVI observed nightglow. Further comparison between the TIMED-GUVI and the F3/C observations shows good agreements in the Southeast Asia, South America, and in the central Pacific regions except that in the Africa, where the north EIA peak is distinct and stronger than the F3/C observed electron density.

4. Discussion and Summary

Both FORMOSAT-3/COSMIC and TIMED-GUVI instruments observed enhanced equatorial ionospheric density in four longitude sectors; South America, Africa, Southeast Asia, and the central Pacific. The locations of these four peaks are similar to those observed by IMAGE-FUV in March Equinox, 2002 during high solar activity conditions [Sagawa et al., 2005; Immel et al., 2006; England et al., 2006a, 2006b]. The F3/C and TIMED-GUVI observations suggest that the coupling process between the nonmigrating tide and the equatorial ionosphere put forward by these authors may also exists near September Equinox during solar minimum conditions.

The most likely wave mode responsible for the four-peaked longitudinal structure is the eastward wavenumber three (E3) diurnal nonmigrating tide [Sagawa et al., 2005; Immel et al., 2006; England et al., 2006a, 2006b]. The E3 diurnal nonmigrating tide, as predicted by the Global Scale Wave Model (GSWM) [Hagan and Forbes, 2002], is excited by latent heat release in the troposphere. When viewing GSWM temperature and wind perturbation maps from a global constant local time (or sun-synchronous) perspective, the E3 diurnal nonmigrating tide exhibits four lower thermospheric or E-region altitude maxima [e.g., Oberheide et al., 2003; Forbes et al., 2006] at the same longitudes of the four strong EIA zones shown in Figure 1 [e.g., Immel et al., 2006; England et al., 2006b]. At the locations of the four peaks, the E3 nonmigrating tidal winds may enhance the Pedersen currents in the E-region, strengthening the daytime eastward electric field produced by E-region dynamo and thus produce a stronger equatorial plasma fountain [e.g., England et al., 2006b]. The stronger equatorial plasma fountain then results in the stronger and poleward-extended EIA in the four regions (see Lin et al. [2005] for detailed discussions of EIA enhancement produced by stronger plasma fountain effect). Additionally, the four-peak locations observed by the F3/C and the TIMED-GUVI are highly correlated with the IMAGE satellite observations, suggesting that a similar atmospheric tide and E-region dynamo coupling process is operating not only in March–April during solar maximum but also in September–October during solar minimum.

The integrated ionospheric electron content in various altitude ranges shown in Figure 3 reveals that the wavenumber-four longitudinal structure becomes discernable above 300 km to 450 km altitude. Averaging the electron density at the northern and southern low-latitude/EIA regions (±3–±15° magnetic latitudes) around globe and
reconstructing altitude versus longitude plots of the electron density in Figure 4 shows that these prominent longitudinal variations exist mainly in the F-region, above 250 km altitude. This vertical structure is important to understand the physical mechanism that is responsible for these variations. Since the wavenumber-four structure is mainly an F-region signature, it supports the hypothesis made by Immel et al. [2006]. That is, the enhanced E-region dynamo electric field, produced by the stronger tidal effect at the four longitude sectors, maps to F-region heights resulting in enhancements of the equatorial plasma fountain and the associated EIA strength.

Additionally, both F3/C and TIMED-GUVI observations show asymmetry between the north and the south EIA peaks in the four-peaked zones. In the Southeast Asia, Africa, and central Pacific, the south EIA peaks are stronger than the north peak, while the north peak is stronger than the south peak in the South America. The two basic processes that affect the EIA formation significantly are the equatorial zonal electric field and thermospheric neutral winds [Balan and Bailey, 1995; Balan et al., 1997; Rishbeth, 2000; Abdu, 2001; Lin et al., 2005]. The equatorial zonal electric field tends to affect the EIA peaks symmetrically since it mainly affects the strength of the plasma fountain resulting in EIA peaks. Thus, the asymmetry in the north and the south EIA peaks seen in Figures 1 and 2 is most likely produced by the asymmetries in neutral winds at F-region altitudes in the two hemispheres. The difference between the South American region and the other three regions in North–South asymmetry may due to the larger magnetic declination angle in the South America region, and thus both the zonal and meridional components of the neutral wind may affect the EIA formation in that region. The longitudinal variation of the EIA strength between the four-peaked zones may result from the asymmetries of the atmospheric tides in the different zones, which produce longitudinal variations in the equatorial zonal electric field. It is also noted that the strength of the magnetic field may contribute to the longitudinal variation of the four high electron density regions.

In summary, the major findings based on FORMOSAT-3/COSMIC and TIMED-GUVI observations presented herein are summarized as follows.

1. The longitudinal variation of the EIA peaks previously seen by IMAGE airglow measurements at 135.6 nm are also observed near September Equinox during solar minimum by both the FORMOSAT-3/COSMIC and the TIMED-GUVI.

2. For the first time the electron density structure of the wavenumber-four longitudinal feature is observed by the FORMOSAT-3/COSMIC in three-dimensions. The locations of the four stronger EIA zones in electron density observed by F3/C are highly correlated with the ionospheric nightglow at 135.6 nm seen by the TIMED-GUVI. Latitudinal asymmetries of the EIA peaks, which vary with longitude, are captured by the two instruments. These may result from longitudinally variable asymmetries in atmospheric tidal effects in the geomagnetic reference frame or from latitude asymmetric F-region neutral wind effects.

3. The four longitude regions of stronger EIA zones observed by the FORMOSAT-3/COSMIC are most significant above 250 km, at F-region heights, suggesting that the feature is most likely produced by physical processes occurring in the F-region.

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