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Traveling planetary wave ionospheric disturbances and their role in the generation of equatorial spread-F and GPS phase fluctuations during the last extreme low solar activity and comparison with high solar activity

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ABSTRACT

This investigation studies traveling planetary wave ionospheric disturbance (TPWID) type oscillations on the modulation of the F region virtual height rise during the $E \times B$ electric field pre-reversal enhancement (PRE), near sunset hours. We also studied their role in the generation of equatorial spread F (ESF) and GPS phase fluctuations during periods of the last extreme low solar activity (LSA) of January 2009 to April 2010 ($\overline{F10.7} = 73$). A comparison is made with periods of high solar activity (HSA) in 2003 and 2004 near equatorial region. The ionospheric irregularities investigated are medium (bottom-side) and large (plasma bubble) scales. Ionospheric F region oscillations with period of days are due to the TPWIDs, which play an important role in producing favorable or unfavorable conditions for equatorial ionospheric irregularities, changing the electron vertical profile and F region height. In this paper, we present simultaneous ionospheric sounding (ionosonde) and GPS vertical total electron content (vTEC) observations carried out near equatorial region (Palmas 10.2°S, 48.2°W) and low latitude region (São José dos Campos 23.2°S, 45.9°W; located under the southern crest of the equatorial ionospheric anomaly), Brazil. Observations show that the occurrence of fresh ESF during LSA and HSA and fresh GPS phase fluctuations at equatorial region follow the trend of day-to-day variations in the F region virtual height, which are due to electric field PRE modulated by TPWID wave like oscillations. During LSA, the altitude of 250 km acts as a threshold height for the generation of fresh ionospheric irregularities, whereas during HSA, the threshold height is 300 km. The observations also found a strong increase in the generation of fresh ionospheric irregularities from October 2009 to March 2010 during LSA and from September 2003 to March 2004 during the HSA. Furthermore, in LSA, the period of fresh ionospheric irregularities was less than during HSA, though both periods followed a similar seasonal pattern. In the low-latitude, we observed more ESFs than phase fluctuations because ionosonde is more sensitive than GPS. We also observed periods with and without day-to-day oscillations in the F region virtual height. The observations made by GPS stations and ionosondes in the equatorial region, for much of the period analyzed, presented similar results with regard to the generation of equatorial ionospheric irregularities. In the low latitude, some nights of January, February, October, and December 2009 also showed a similarity.

1. Introduction

The day-to-day variability of the ionosphere during geomagnetically quiet periods has been commonly related to oscillations of gravity waves (GWs) and planetary waves (PWs). The PWs are oscillations of predominantly tropospheric origin and have global scales with periods ranging from 2 to 30 days (Lastovicka and Sauli, 1999). However, Fagundes et al. (2005) proposed that ionospheric oscillations with period of 24–30 days and 9–17 days are related with solar rotation and half solar rotation, respectively. The day-to-day variability of the ionosphere based on both modeling and observational results with emphasis being paid to the role of

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PW activity on the day-to-day variability, has been extensively provided by Mendillo et al. (2002), Lastovicka et al. (2003), Abdu et al. (2006a,2006b), Fagundes et al. (2009a,2009b), Takahashi et al. (2006,2007), Borries et al. (2007), Pedatella and Forbes (2009), Chang et al. (2010), and Liu et al. (2010). Mendillo et al. (2002), using TIME-GCM model, reported excellent studies of the day-to-day variability of the ionospheric F region. Takahashi et al. (2006) detected periodicities between 3 and 6 days propagating upwards from the lower thermosphere to the ionosphere, modulating the F region dynamo. Borries et al. (2007) investigated the ionospheric region using GPS TEC maps, and they observed oscillations with large amplitudes due to the presence of PWs. Fagundes et al. (2009a,2009b) detected oscillations with periods of days in the evening F region virtual height and equatorial spread-F, during high solar activity period, and they attributed these oscillations to the traveling planetary wave ionospheric disturbances (TPWIDs).

In the equatorial and low latitude regions, these waves could explain the day-to-day variability in the generation of equatorial spread-F (ESF). Theoretical and experimental studies have established that the fundamental mechanism of equatorial ionospheric irregularities is the Rayleigh–Taylor instability (R–T) acting in the F region bottom-side after sunset, which creates small perturbations in the electron density (Sultan, 1996; Saito and Maruyama, 2006). However, the major issue in the R–T instability is the identification of a precursor that could lead to its starting process. Many researchers have indicated that the GWs are the best candidate for this purpose (e.g., Kelley et al., 1981; Sekar et al., 1995; Sastri et al., 1997; Lin et al., 2005), but the relationship between GW and ESF generation is not yet completely established. Therefore, the presence of TPWID type oscillations could modulate the uplifting of the F region virtual height during electric field pre-reversal enhancement (PRE), creating favorable or unfavorable conditions to generate ESF. The ionospheric irregularities, recorded commonly on ionograms, are called spread-F and differ between themselves in frequency and range types when detected by ionosonde. Frequency type is associated with narrow spectrum irregularities, and range type is associated with wide irregularities or the development of plasma bubbles (Abdu et al., 2003). On the other hand, the phase fluctuations or rate of change of TEC from Global Positioning System (GPS) observations indicate the presence of large-scale ionospheric irregularities, of the order of kilometers (Aarons et al., 1996). The ionospheric irregularities in different longitudes have been investigated by many researchers during geomagnetically quiet and disturbed periods using several instruments including ionosonde and GPS observations. Chen et al. (2006) using ionosonde and GPS receiver analyzed the equatorial F region irregularities in western South America, and they showed that the GPS phase fluctuations can represent the appearance of the ionosonde spread-F, and the strong level of GPS phase fluctuations are associated with the occurrence of topside plasma bubbles/large scale F-region irregularities. Lee et al. (2009) recorded ionograms with spread-F traces and GPS phase fluctuations near the crest of equatorial ionization anomaly (EIA) during 2000. Their investigation indicated that the F region irregularities are responsible for the spread-F traces and TEC rate of change at the EIA.

Thus, in this paper we present and discuss observations of traveling planetary wave ionospheric disturbance (TPWID) type oscillations, with periods of several days, during the extreme low solar activity (LSA) period from January 2009 to April 2010 ($\overline{F10.7} = 73$ [W/m^2 Hz]). Then we compare the present results with high solar activity (HSA) periods of 2003 and 2004. The TPWIDs act on the modulation of the F region virtual post-sunset height rise during the $E \times B$ electric field PRE and, consequently, the generation of equatorial spread-F and phase fluctuations. This investigation is focalized mainly with the conditions for generation and the onset time of equatorial ionospheric irregularities. Therefore, only spread-F and phase fluctuations observed between 1800 LT and 2100 LT, identified as fresh irregularities, generated near the observation site are considered. Spread-F and phase fluctuations observed later are identified as fossil irregularities, generated far away from the site which drifted eastward reaching the observation site after 2100 LT (Saito and Maruyama, 2006). For the present investigation, we used the F region virtual height for five different frequencies (iso-frequencies) measured by digital ionosonde, the vertical total electron content (vTEC), and the phase fluctuations (rate of change of TEC) measured by GPS. Both virtual height and vTEC were obtained during evening hours (1900 LT and 2000 LT), carried out at Palmas (10.2°S, 48.2°W, dip latitude 5.5°S; hereafter referred as PAL), near equatorial region, and São José dos Campos (23.2°S, 45.9°W, dip latitude 17.6°S; hereafter referred as SJC), under the southern crest of the equatorial ionization anomaly (EIA), Brazil. To the best of our knowledge, this is the first investigation of the TPWID type oscillations and their role on the generation of equatorial ionospheric irregularities emphasizing the equatorial and low-latitude regions in the Brazilian sector.

2. Observations and methodology

The ionospheric data used in this investigation were obtained at PAL and SJC, both sites locate in the Brazilian sector. The geometry configuration of these sites allows simultaneous study of the time evolution of electric field PRE near equatorial region (PAL) and its effect at low-latitude (SJC). Both ionosondes and GPS receivers were strategically positioned almost aligned along the magnetic meridian (see Fig. 1 for more details). These ionosonde and GPS sites geometric configurations are very useful to study the ionospheric plasma electrodynamics along the Earth's magnetic field.

In this investigation we analyzed ionospheric sounding data obtained at PAL and SJC stations, Brazil, by two digital ionosondes of the type Canadian Advanced Digital Ionosonde (CADI), operated by the "Universidade do Vale do Paraíba (UNIVAP)" network (Grant et al., 1995; Sahai et al., 2007a, 2009a, 2009b; de Jesus et al., 2011; Klimenko et al., 2011). The ionosonde operates simultaneously in two different modes. The first mode scans 180 frequencies every 300 s (provides normal ionograms with temporal resolution of 300 s) and the second mode scans only 6 fixed frequencies (3, 4, 5, 6, 7, and 8 MHz) every 100 s (ionograms with lower spectral resolution, but with high temporal resolution of 100 s). The second mode of operation was utilized to examine the day-to-day variability of the F region virtual height at 5 fixed frequencies (3, 4, 5, 6, and 7 MHz).

We also used Global Positioning System (GPS) observations obtained at PAL and SJC stations. The PAL station belongs to the "Rede Brasileira de Monitoramento Contínuo (RBMC)" and is operated by the "Instituto Brasileiro de Geografia e Estatística (IBGE)" and the SJC station belongs to the UNIVAP network. The GPS observations were used to measure the vertical total electron content (vTEC) calculated in units of TEC (1 TECU = 10^{16} electrons/m^2) and of the phase fluctuations or rate of change of TEC calculated in TECU/min (Sahai et al., 2009c; de Abreu et al., 2010a, 2011; de Jesus et al., 2010, 2012). The GPS observations used to measure the vTEC were obtained from the GPS satellites above 20° elevation angle and temporal resolution of 15 s (PAL) and 5 s (SJC).

The methodology applied in this investigation is described by Fagundes et al. (2005,2009a,2009b) for studying TPWID type oscillations at F region virtual height. We selected the F region virtual height for each day considered in this analysis at 19:00 LT and 20:00 LT for 5 frequencies (3, 4, 5, 6, and 7 MHz) for the period