Journal of Atmospheric and Solar-Terrestrial Physics 135 (2015) 22–35

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

TEC variation during high and low solar activities over South American sector

O.F. Jonah[a], E.R. de Paula[a], M.T.A.H. Muella[b], S.L.G. Dutra[a], E.A. Kherani[a], P.M.S. Negreti[a], Y. Otsuka[c]

[a] Instituto Nacional de Pesquisas Espaciais (INPE), Av. de Astronautas, 1758, Jd da Granja, São José dos Campos, São Paulo 12227-010, Brazil
[b] Instituto de Pesquisa e Desenvolvimento (IP&D), Universidade do Vale do Paraíba (UNIVAP), Av. Shishima Hifumi, 2911, São José dos Campos, São Paulo 12444-000, Brazil
[c] Nagoya University, 3-13 Honohara, Toyokawa, Aichi 442-8507, Japan

ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form
1 October 2015
Accepted 4 October 2015
Available online 9 October 2015

Keywords:
Total Electron Content (TEC)
Diurnal, seasonal, latitudinal and longitudinal variations of TEC
TEC periodicity during high and low solar activities
Equatorial Ionization anomaly at different seasons

ABSTRACT

Using dual frequency GPS receivers in the South American sector, the measurement of absolute ionospheric Total Electron Content (TEC) has been estimated applying the Nagoya ionospheric model for both the years of 2009 and 2001, which represent low and high solar activities, respectively. The diurnal, day-to-day, monthly, seasonal, latitudinal and longitudinal variations of TEC were studied for equatorial and low latitude regions of South America. The strength and characteristics of the Equatorial Ionization Anomaly (EIA) were equally analyzed. The analyses reveal the diurnal, seasonal and semidiurnal TEC variation, as well as the nighttime variability during the low and high solar activities. Wavelet power spectra analysis was employed to check the periodicities of the TEC data, F10.7 and zonal and meridional wind velocities measured by Meteor radar at ~100 km altitude. Periods such as 27, 16, 8–10, 1–5 days were found to be dominant in the zonal and meridional wind velocity corresponding with those of TEC periodicities. Hence, besides the solar radiation, we suggest that there are contributions of tides and planetary waves in spatial and temporal TEC enhancement and variations during the geomagnetic quiet periods of both solar activities.

1. Introduction

Exploring the ionosphere is of utmost interest due to the numerous complexities associated with this region (Rabiu et al., 2007). Although, over the last century humanity has learned to use the properties of the ionosphere in a tremendous way, there are more to understand about the chemical and physical changes of this region of the Earth's atmosphere. One of the parameters that can be used to study the ionosphere is the Total Electron Content (TEC). Study of TEC variability over the South American continent is of great interest due to the possibility to investigate the processes responsible for the ionospheric behavior over this region. TEC is significant in helping us to understand the short and long term changes of our upper atmosphere during major phenomena caused by factors like solar activities, geomagnetic storms and meteorological influences (e.g. Forbes et al., 2000; Kane, 2003; Rishbeth and Mendillo, 2001). These changes in the ionosphere affect navigation systems, surveillance systems and modern technologies such as communication systems, since the signal from the satellite to the receiver must pass through the ionized layer (Bagiya et al., 2009), which causes a delay at such signal. A good description of the ionosphere is also needed in order to improve the performance of the ionospheric models (Bilitza, 2000).

Many researchers have studied the morphological features of ionospheric electron density and TEC at low and equatorial latitudes (Dabas et al., 1993; Kane, 2003; Batista and Abdu, 2004; Costa et al., 2004; Rama Rao et al., 2006; Bhuyan and Borah, 2007; Abdu et al., 2007; Bagiya et al., 2009, Jonah et al., 2014, Duarte-Silva et al., 2015). Dabas et al. (1993) studied the variations in TEC with different solar indices, i.e. EUV, F10.7 solar flux and smoothed sunspot number (SSN) for summer, winter and equinoxes over the Indian sector. They showed that TEC exhibited nonlinear relationship with SSN in general and linear variations with EUV and F10.7 solar flux. Kane (2003) studied day-to-day variability of quiet-time ionosphere using F2-peak electron density data. He observed oscillations of day-to-day variation with peak spacing of ~7 days at several locations and indicated that in the absence of solar or geomagnetic effects, planetary waves dominate the day-to-day variability. Batista and Abdu (2004) also studied the ionospheric variability from observations of the F2 layer peak density over the Brazilian low and equatorial latitudes. Costa et al. (2004) investigated diurnal and seasonal variations of TEC during a year of low solar activity (1997) at Presidente Prudente, a station located

http://dx.doi.org/10.1016/j.jastp.2015.10.005
1364-6826/© 2015 Elsevier Ltd. All rights reserved.

near the equatorial ionization anomaly crest in Brazil. It was found that TEC was maximum during summer months (from November to February) and minimum during winter months (from May to August), with intermediate values during the equinoctial months, but the springer equinox (September–October) presenting larger TEC values than the autumn equinox (March–April). Bhuyan and Borah (2007) reported that the ionospheric diurnal variability is in general less significant at the magnetic equator, and tend to increase progressively towards the crest regions of the equatorial ionization anomaly. Abdu et al. (2007) studied the solar flux effects on equatorial ionization anomaly and total electron content over Brazil, using maximum frequency of F2 layer (foF2) data set between 1996 and 2003 and TEC data set between 2002 and 2003. They found similar solar flux dependence of seasonal variation in both foF2 and TEC, which showed maximum during equinox and minimum during June solstice. Solar activity dependence of TEC has also been studied by a large number of researchers (e.g. Balan et al., 1993 and references cited there in). We also highlight the climatologic studies derived from TOPEX/POSEIDON measurements (e.g. Codrescu et al., 1999, 2001; Jee et al., 2004; Scherliess et al., 2008) which established many interesting facts about longitudinal, seasonal, wave number four, and geomagnetic TEC variations.

The South American sector is associated with highly variable electrodynamics processes which are particularly prominent at the equatorial and low-latitude regions. The declination of the magnetic field lines is the highest at the Brazilian region and gradient between the trough and the crest is very sharp, which results in large temporal and spatial variation of the ionospheric electron content (Dasgupta et al., 2007; Muella et al., 2010). The largest fraction of the solar radiant energy is also centered mainly at the equatorial and low latitudes, hence many interesting phenomena are presented at these regions. However, other effects associated to the strength of the equatorial electrojet (EEJ), changes of the Earth's magnetic field at the South American Magnetic Anomaly region (SAMA), added to the effects of tides, waves and the thermospheric neutral winds contribute to the variability in TEC.

The ionospheric electron density variability during geomagnetic disturbed times have been observed by numerous authors (e.g. Fedrizzi et al., 2001; Tsurutani et al., 2008; de Siqueira et al., 2011), and only few studies (e.g. Jee et al., 2004; Scherliess et al., 2008) have been reported for quiet time period. Yet the motions in the upper atmosphere are of two kinds, those whose immediate sources of energy are confined in the upper atmosphere itself, and those whose energy are transmitted from the lower atmosphere (Charney and Drazin, 1961). Hence, this study aims at generally understanding the TEC variations during geomagnetic quiet time at the ionospheric region of the South America sector.

This present paper is organized in the following way: Firstly describe the data and methodology used to estimate the absolute GPS total electron content by using the Nagoya ionospheric model. Next, in Section 3, we present the results and the discussions on the diurnal, monthly and seasonal variations of TEC during a year of high solar activity (2001) and a year of low solar activity (2009), and also on the periodicities of TEC. Finally, in Section 4, we present the conclusions.

2. GPS-TEC measurement methodology and data

The Absolute TEC (ATEC) used in the work was estimated from the Nagoya model by making use of the following principal equations (Otsuka et al., 2002). The slant TEC at a piercing point is mapped to the vertical TEC (VTEC) at that point and it is given by

$$T^i(t) = S(\varepsilon^i(t))V^i(t), \tag{1}$$

where $\varepsilon^i = \varepsilon^i(t)$ is the elevation angle of the GPS satellite, $V^i(t)$ is the vertical TEC, $S(\varepsilon^i(t))$ is the slant factor (mapping function) given by τ_i/τ_o, and τ_i is the oblique length of ray path between 300 and 550 km altitude while τ_o is equal to the ionospheric thickness of 250 km for zenith path. In order to eliminate errors, which increase relative to the slant factor, the cutoff elevation angle was fixed at 30°. The absolute $TECI^i(t)$, measured by satellite-i at epoch t, can therefore be obtained by equation:

$$I^i(t) = S(\varepsilon^i(t))V^i(t) + B^i \tag{2}$$

where B^i is the instrumental biases of both the receiver and the satellite. The B^i is calculated by using the least square fitting method as shown by the following residual equation:

$$E = \sum_i^{N_S}\sum_k^{N_i} W_k^i\left[\frac{\bar{I}_k}{S(\epsilon_k^i)} - \left(\overline{V_k} + \left(\frac{1}{\overline{S(\epsilon_k^i)}}\right)B^i\right)\right]^2, \quad W_k^i = \frac{1}{S(\epsilon_k^i)} \tag{3}$$

where W_k^i is the weighting function, V_k, $k = 1,2,\ldots,N_t$ and B^i, $i = 1,2,\ldots,N_s$ where N_t is the number of hourly TEC average, and N_s is the number of satellites which are observed by a receiver (note that variables with overline denote averaged values). Taking the partial derivatives of E with respect to V_k and B^i, and setting them to zero, yield equations which can be solved for the desired parameters (V_k and B^i). To reduce the estimation errors of hourly TEC average caused by the assumptions of both the shell model and the spatial uniformity of the hourly TEC average, W_k^i is selected as an inverse of the slant factor (second part of Eq. (3)) and it becomes smaller with decreasing elevation angle. For further explanation readers are referred to Otsuka et al. (2002).

In order to study the variation of TEC due to local time, season and solar activity over South America sector, we have obtained data from the following data bases:

1. SOPAC: Scripts and Permanent Array Centre Garner GPS archive (known as SOPAC GARNER) contains files of observation and navigation from the GPS global network. The data base belongs to the International GNSS Service (IGS). It is available at ⟨ftp://garner.ucsd.edu/pub/rinex/⟩.
2. RBMC/IBGE: Brazilian Network for Continuous Monitoring of the Institute of Brazilian Geography and Statistics. The data of this database can be accessed at ⟨ftp://geoftp.ibge.gov.br/RBMC/dados/⟩.

The distribution of the ground-based dual frequency GPS receivers used in this work are given in Fig. 1. The F10.7 cm solar flux and Kp data were obtained from the National Geophysical Data Center (NGDC) at National Oceanic and Atmospheric Administration (NOAA) data base (http://omniweb.gsfc.nasa.gov/form/dx1.html). In the top panel of Fig. 2 is shown the F10.7 cm solar flux in sfu (1 sfu $= 10^{-22}$ W m^{-2} Hz^{-1}) from 2000 to 2009. In the middle and bottom panels of Fig. 2 are shown the daily $\sum$Kp index throughout 2001 and 2009, respectively. Only data from daily $\sum\mathrm{Kp} \leq 24$ were considered in this work.

The MLT wind data measured at Santa Maria (29.4°S, 53.3°W, dip latitude 17.8°S) and Cachoeira Paulista (22°S, 45°W, dip latitude 15°S) are used to infer the meridional and zonal wind. The meteor radar system is an All-Sky Interferometric Meteor Radar (SKiYMET) type with operating frequency of 35.24 MHz. It utilizes 13 pulse width, with a peak power of 12 kW and pulse repetition frequency of 2 kHz. Due to practical limitations, the received data are obtained within the zenith angle range 17–70°, since at lower zenith angle (< 15°) radial velocity errors are excessive and at higher zenith angle (> 70°) the signal gets contaminated with ground clutter and airplane echoes. The radar detects about 5000 meteor echoes per day for which it estimates angular position,