Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 60 (2017) 257–275

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Seasonal and solar cycle effects on TEC at 95°E in the ascending half (2009–2014) of the subdued solar cycle 24: Consistent underestimation by IRI 2012

Geetashree Kakoti, Pradip Kumar Bhuyan *, Rumajyoti Hazarika

Centre for Atmospheric Studies, Dibrugarh University, Dibrugarh 786004, India

Received 12 April 2016; received in revised form 2 September 2016; accepted 4 September 2016
Available online 10 September 2016

Abstract

TEC measured at Dibrugarh (27.5°N, 94.9°E, 17.5°N Geomag.) from 2009 to 2014 is used to study its temporal characteristics during the ascending half of solar cycle 24. The measurements provide an opportunity to assess the diurnal, seasonal and longterm predictability of the IRI 2012 (with IRI Nequick, IRI01-corr, IRI 2001topside options) during this solar cycle which is distinctively low in magnitude compared to the previous cycles. The low latitude station Dibrugarh is normally located at the poleward edge of the northern EIA. A semi-annual variation in GPS TEC is observed with the peaks occurring in the equinoxes. The peak in spring (March, April) is higher than that in autumn (September, October) irrespective of the year of observation. The spring autumn asymmetry is also observed in IRI TEC. In contrast, the winter (November, December, January, February) anomaly is evident only in high activity years. TEC bears a distinct nonlinear relationship with 10.7 cm solar flux ($F_{10.7}$). TEC increases linearly with $F_{10.7}$ up to about 125 sfu beyond which it tends to saturate. The correlation between TEC and solar flux is found to be a function of local time and peaks at 10:00 LT. TEC varies non-linearly with solar EUV flux similar to its variation with $F_{10.7}$. The nonlinearity is well captured by the IRI. The saturation of TEC at high solar activity is attributed to the inability of the ionosphere to accommodate more ionization after it reaches the level of saturation ion pressure. Annual mean TEC increased from the minimum in 2009 almost linearly till 2012, remains at the same level in 2013 and then increased again in 2014. IRI TEC shows a linear increase from 2009 to 2014. IRI01-corr and IRI-NeQuick TEC are nearly equal at all local times, season and year of observation while IRI-2001 simulated TEC are always higher than that simulated by the other two versions. The IRI 2012 underestimates the TEC at about all local times except for a few hours in the midday in all season or year of observation. The discrepancy between model and measured TEC is high in spring and in the evening hours. The consistent underestimation of the TEC at this longitude by the IRI may be attributed to the inadequate ingestion of F region data from this longitude sector into the model and exclusion of the plasmaspheric content.

Keywords: TEC; IRI; Equinoctial asymmetry; Winter anomaly; Solar cycle

1. Introduction

The total electron content (TEC) is the height integrated electron density along the ray path from the satellite to the receiver and its variation with time and space provides an instantaneous description of the intervening ionosphere. It is a key parameter in many space weather applications. The ionosphere induced range and time delay errors in any trans-ionospheric satellite radio communication is proportional to the total electron content along the ray path. Measurement of TEC under different geophysical conditions with high accuracy and temporal resolution has

* Corresponding author.
E-mail addresses: bhuyan@dibru.ac.in, pkbhuyan@gmail.com (P.K. Bhuyan).

http://dx.doi.org/10.1016/j.asr.2016.09.002
0273-1177/

become important because of the increasing demand on satellite, aircraft or ground based navigation based on trans-ionospheric communication systems. As the three processes of production, loss and transport control the distribution of plasma in the earth's ionosphere, TEC is subjected to substantial day-to-day variability particularly at equatorial and low latitudes. The equatorial and low latitude ionosphere is significantly different from the middle and high latitude ionosphere and exhibits many unique features in density and temperature such as the plasma fountain, equatorial ionization anomaly (EIA), and the equatorial electrojet (EEJ). The EIA, a depression in ionization densities or trough at the equator and two peaks at about $\pm 17°$ magnetic latitude was first reported by Appleton (1946). The daytime eastward electric field, together with the horizontally northward magnetic field, forces plasma upward (Martyn, 1947). As the plasma is sifted to greater heights, it diffuses downward along magnetic field lines under the twin action of gravity and pressure gradients (Hanson and Moffett, 1966). A plasma fountain thus forms which moves ionization from the magnetic equator to the two anomaly crests. After sunset, as the electric field reverses in direction, the F region plasma drifts downward and the fountain reverses and the crests disappear. The fountain rises to several hundred kilometers at the equator and the crests become weaker with increase in altitude. At higher altitude, a single crest of ionization is formed over the equator (Su et al., 1995; Balan and Bailey, 1995). The horizontal orientation of the geomagnetic field lines at the equator, which inhibits vertical transport and heat flow and the shift between the geographic, and geomagnetic equator produces latitudinal and longitudinal variations. The location of the anomaly peak shifts towards higher latitudes with increase in $E \times B$ drift velocity. Asymmetric neutral winds about the equator produce a north south asymmetry in the EIA (Balan and Bailey, 1995). The occurrence of the anomaly crest and its strength are found to have diurnal, monthly, seasonal and solar activity variations (Rush and Richmond, 1973; Bhuyan and Bhuyan, 2009) as well as variation with geomagnetic activity (Su et al., 1995). During high solar activity periods the crest of the anomaly in the Indian zone shifts towards high latitudes and during low solar activity, it shifts towards low latitudes (Chakraborty and Hajra, 2009).

Global distribution of TEC as well as its characteristics at equatorial, middle and high latitudes has been investigated by a number of workers using GPS time delay measurements over the last few decades (references in Bhuyan and Borah, 2007). The GPS is a satellite based positioning system widely used for navigation, relative positioning and time transfer. The relative time delay of the 1.57542 GHz (L1) and 1.22760 GHz (L2) simultaneous transmissions from GPS satellites by the dispersive ionosphere can be converted into TEC. The dual frequency GPS receiver provides a means of monitoring the effect of the ionosphere on GPS signals. Simultaneous measurement of L1 and L2 frequencies permit measurement of the relative phase delay between the two signals, giving an unambiguous slant TEC. Davies and Hartmann (1997) noted that TEC measurements are useful for the study of long-term behavior, day to day fluctuations and storm time effects of the ionosphere. Thus although the GPS was originally developed to serve as a radio navigation satellite system, it is now widely used for many other scientific and technological applications. As the GPS signals traverse the ionosphere carrying signatures of the dynamic medium, GPS TEC measurements offer unique opportunity for studying the temporal and spatial distribution. Global and regional maps of electron content were produced using data from the worldwide network of the International GPS Service (IGS). It may be noted that the global ionospheric TEC maps are still produced with lot of data gaps particularly over the oceans and the Indian subcontinent, west Asia including northern Africa (http://iono.jpl.-nasa.gov//latest_rti_global.html). GPS TEC has also been used for tomographic imaging of the ionosphere (e.g. Tsai et al., 2002; Chen and Saito, 2016).

Though the characteristics of TEC in the Indian equatorial and low latitude region has been studied and reported by a number of workers using the TEC data obtained from radio beacons on board geostationary satellites (e.g. Davies, 1980; Sethia et al., 1980; Dabas et al., 1984; Rastogi and Alex, 1987; Bhuyan et al., 1983; Gupta and Singh, 2000), with the advent of the GPS a new era in TEC measurement and application has become possible. A joint coordinated program under the project GAGAN (Geo and GPS Augmented Navigation), the Indian Space Research Organization and Airport Authority of India launched the Indian version of Wide Area Augmentation System (WAAS), to monitor TEC at eighteen locations across India using GPS satellites in 2003. The chain of GPS receivers provided an opportunity to attempt an extensive study of the Indian zone TEC with high temporal and spatial resolution (Rama Rao et al., 2006; Bhuyan and Borah, 2007). Bagiya et al. (2009) reported the temporal variations of GPS TEC at Rajkot (14.03°N Geomag.) near the EIA crest region in India for the period 2005–2007. Kumar and Singh (2011) have studied the storm time response of GPS derived TEC during the low solar activity period of 2007–2008 at an Indian low latitude station, Varanasi ($\sim$15°N, Geomag.) near the crest of the EIA. Kumar et al. (2014a) studied the TEC variability around the EIA crest using GPS measurements at two locations in the Indian equatorial anomaly region Varanasi and Kanpur ($\sim$17.55°N, Geomag.).

The International Reference Ionosphere (IRI) is the international standard model for the ionosphere and validation of the model against data obtained in different and distinctive time space domains is required in order to use the model as an alternative to measurements. However, discrepancies between observation and IRI simulations have not been overcome as yet. Lühr and Xiong (2010) have found considerable inconsistencies between in situ electron density measurements by the CHAMP and