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Imaging Global Electron Content backwards in time more than 160 years ago

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Abstract

The Global Electron Content, GEC, represents the total number of electrons in the spherical layer over the Earth restricted by orbit of Global Positioning Satellite system (20,200 km). GEC is produced from Global Ionospheric Map of Total Electron Content, GIM-TEC, transformed to the electron density varying with height using the International Reference Ionosphere and Plasmasphere model, IRI-Plas. The climatologic GEC model is developed from GIM-TEC maps for a period 1999–2012 including the solar activity, annual and semi-annual cycles as the most important factors affecting daily GEC variation. The proxy R_{zp} of the international sunspot numbers, R_i, is used as a measure of solar activity composed of 3 day smoothed R_i, 7 day and 81 day backwards mean of R_i scaled to the range of 1–40 proxy units, p.u. The root mean square error of the GEC climatologic model is found to vary from 8% to 13% of GEC. Taking advantage of a long history of sunspot numbers, the climatologic GEC model is applied for GEC reconstruction backwards in time for more than 160 years ago since 1850. The extended set of GEC values provides the numerical representation of the ionosphere and plasmasphere electron content coherent with variations of solar activity as a potential proxy index driving the ionosphere models.

Keywords: Global Electron Content; Proxy sunspot number; Ionosphere-Plasmasphere IRI-Plas model

1. Introduction

Data from Global Ionospheric Maps of Total Electron Content, GIM-TEC, provided by the International GNSS Service (IGS) opens an opportunity to investigate the long-term and short-term variations in the ionosphere and plasmasphere on global scale. The planetary averaged F2 layer critical frequency (Lal, 1997), the global mean TEC (Zhao et al., 2007; Hocke, 2008; Liu et al., 2009; Scharroo and Smith, 2010; Lean et al., 2011; Li et al., 2013) and the Global Electron Content, GEC (Afraimovich et al., 2006, 2008; Astafyeva et al., 2008; Gulyaeva and Veselovsky, 2012) are successfully applied for the global ionosphere investigations. The Global Electron Content, GEC, represents a single value over the globe integrating the total electron content in the spherical segment from the bottom of ionosphere (65–80 km) to GPS satellites orbit (20,200 km) in the plasmasphere. With growing implementation of the GNSS data in space research and industry, the properly modeled GEC parameter could provide new option for the ionospheric index of solar activity.

The ionospheric index of solar activity has been invented more than 50 years ago (Minnis, 1955). It was afterwards improved by Liu et al. (1983) based on the noon F2 layer critical frequency, foF2, from 13 ionosondes worldwide. The latter index called the ionospheric global IG index is still routinely produced and predicted at (http://www.wdc.rl.ac.uk/wdcc1/monthly_reports.html) but currently it is based on the data of only four ionospheric stations since most of the former 13 stations ceased operating lately. The 12 months smoothed IG12 index is

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used as a driving index by the International Reference Ionosphere, IRI, model though its reliability against the sunspot numbers R12 become uncertain, in particular, an appreciable divergence of these two indices during the recent prolonged solar minimum was found suggesting a need for their revision (Bilitza et al., 2013). The time has come to improve the former ionospheric indices of solar activity based on data of a limited number of ionosondes (Minnis, 1955; Liu et al., 1983; Mikhailov and Mikhailov, 1995) by a novel planetary scale index.

It has been noted that the use of the global electron content or global average TEC as a new index of solar activity (SA) is promising since it reflects the changes in solar activity and correlates very well with solar extreme ultraviolet (EUV) radiation (Afraimovich et al., 2008; Hocke, 2008; Scharroo and Smith, 2010). However, a linear implementation of the correlation of GEC with the solar activity alone (Afraimovich et al., 2006, 2008) does not reflect annual, semi-annual and other components of GEC and TEC variability. Departures of the ionospheric climatology from direct solar control are widely discussed in the literature (Lal, 1997; Rishbeth and Muller-Wodarg, 2006; Zhao et al., 2007; Hocke, 2008; Liu and Chen, 2009; Scharroo and Smith, 2010; Lean et al., 2011; Li et al., 2013). Also, to become compatible with available ionospheric indices of solar activity based on measurements of a limited number of ionosondes (Minnis, 1955; Liu et al., 1983; Mikhailov and Mikhailov, 1995) the GEC (or global mean TEC) should overcome a limited history of GIM-TEC production originated at mid-1990s which suggests a need for its modeling and restoration for a longer period.

The purpose of the present study is development of the climatologic GEC model in terms of three main driving parameters detected earlier with GIM-TEC analysis (Zhao et al., 2007; Lean et al., 2011; Li et al., 2013): solar activity, annual and semi-annual GEC variations. The present analysis is based on GEC products obtained from available GIM-TEC maps for 1999–2012, and the resulting model is applied for reconstruction of GEC for a longer period in the past.

Comparison of the different solar proxies and indices for the prediction of global TEC has given a favor to complex solar proxies comprising a combination of 3 day smoothed sunspot number, SSN, centered on the given day, 7 day backward mean and 81 day backward mean (Maruyama, 2010). So far, among other solar activity proxies available for studying the solar activity, the main international sunspot time series, R_i, are the most extended and go back to 1849 (Lefevre and Clette, 2013).

Further progress in an investigation of the statistical relations between the different solar and interplanetary parameters is reached by scaling the base proxy index within the range of the denser proxy values (Laptukhov et al., 2009). Accordingly, we proceed with development of GEC model based on the international sunspot numbers, R_i, applying their proxy combination of 3 day mean, 7 and 81 backwards days mean, and scaled to the proxy R_{zp} varying within the range from 1 to 40 p.u. (proxy units). Model of GEC(R_{zp}) is produced for each month (day-of-year) and applied for GEC reconstruction from 1850 onwards. The GEC production from GIM-TEC database, GEC model derivation and results are provided in the next sections.

2. GEC production from GIM-TEC database

The Global Ionospheric Maps of Total Electron Content calculations are based on measurements of the integral total electron content, TEC, by the satellite navigation GPS system, permanently recorded in the world-wide observation network, and generalized in several global data centers in the form of Global Ionospheric Maps, GIM-TEC, in which TEC is prescribed as a function of time and location. GIM-TEC maps produced by Jet Propulson Laboratory (Mannucci et al., 1998) are used in the present study for a period from 1999 to 2013 for calculation of Global Electron Content through the ionosphere and plasmasphere. The GIM-TEC maps are routinely converted to 3-D electron density profile with the International Reference Ionosphere – Plasmasphere model (Gulyaeva et al., 2011, 2013).

The parameter of Global Electron Content (GEC) has been introduced by Afraimovich et al. (2006, 2008). By definition, GEC is equal to the total number of electrons in the near-Earth space limited by the orbit height of the navigation satellites of Global Positioning GPS system, 20,200 km. The advantage of GEC parameter is the possibility to analyze the state and variability of the ionosphere and the plasmasphere as a whole similar to planetary averaged the F2 layer ionization (Lal, 1997), global mean TEC (Zhao et al., 2007; Hocke, 2008; Scharroo and Smith, 2010; Lean et al., 2011; Li et al., 2013) and the planetary derived the ionosphere storm index (Gulyaeva and Stanislwska, 2008), while most other parameters are bound to local or regional features of the near-Earth plasma. TEC is measured in TEC units, TECU = 10^{16} el m^{-2}, each value indicates the number of free electrons in a column of unit cross section from the lower boundary of the ionosphere above the Earth (65–80 km) to the GPS navigation satellites orbit, 20,200 km. Similar to unit of TEC measure, a measure of GEC is introduced, GECU = 10^{32} el.

For selected moments of the universal time GIM maps are produced with a two-hour time resolution, since July 1998, and a one-hour time intervals from December 2008 up-to-date available on the Internet in IONEX format. Each GIM map contains 5183 TEC values in cells of size of 2.5° in latitude [$-90° < \varphi < 90°$], and 5° in longitude [$-180° < \lambda < 180°$]. The local time features are masked in GEC product for every universal time, UT, hour, map. So we proceed to analysis of daily mean GEC against single daily sunspot number proxy.

In the initial papers (Afraimovich et al., 2006, 2008) the GEC was determined by summing of the total electron content, TEC, in each map cell, multiplied by the area of the