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Global structure of ionospheric TEC anomalies driven by geomagnetic storms

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ABSTRACT

This study examines the structure and variability of the ionospheric TEC anomalies driven by geomagnetic storms. For this purpose the CODE global ionospheric TEC data from four geomagnetically disturbed periods (29 October–1 November 2003, 7–10 November 2004, 14–15 December 2006, and 5–6 August 2011) have been considered. By applying the tidal analysis to the geomagnetically forced TEC anomalies we made an attempt to identify the tidal or stationary planetary wave (SPW) signatures that may contribute to the generation of these anomalies. It has been found that three types of positive anomalies with different origin and different latitudinal appearance are observed. These are: (i) anomalies located near latitudes of ±40° and related to the enhancement and poleward moving of the equatorial ionization anomaly (EIA) crests; (ii) anomalies located near latitudes of ±60° and seen predominantly in the night-side ionosphere, and (iii) very high latitude anomalies having mainly zonally symmetric structure and related to the auroral heating and thermospheric expansion. The decomposition analysis revealed that these anomalies can be reconstructed as a result of superposition of the following components: zonal mean (ZM), diurnal migrating (DW1), zonally symmetric diurnal (D0), and stationary planetary wave 1 (SPW1).

1. Introduction

During the geomagnetic disturbances, which are excited through the interaction between coronal mass ejections (CMEs) and the Earth's magnetic field, the energy inputs lead to substantial effects in the upper atmosphere and the ionosphere. One of these effects is the significant perturbation of the “quiet-time” ionosphere due to large variability in the ionospheric density distribution, total electron content (TEC), and the ionospheric current system. The rapid and global response of the ionosphere to these strong geomagnetic disturbances is well studied (Mendillo et al., 1970, 1992; Prölss, 1980, 1991, 1993, 1995, 2008; Rishbeth, 1991, 1998; Field and Rishbeth, 1997; Fuller-Rowell et al., 1994, 1996, 2000; Muhtarov and Kutiev, 1998; Buonsanto, 1999; Kutiev and Muhtarov, 2001, 2003; Jakowski et al., 2005; Mendillo, 2006; Trichtchenko et al., 2007; Stankov et al., 2010; Balan et al., 2010, 2011).

During intense geomagnetic storms drastic modifications to dynamics, electrodynamics and chemistry of the Earth's atmosphere-ionosphere system take place on a global scale. Three dominant causes of storm effects have been suggested to explain the positive and negative phases of ionospheric storms: thermospheric composition changes, neutral wind perturbations and the appearance of electric fields of magnetospheric origin (Mendillo, 2006). Satellite neutral mass spectrometer measurements showed that the negative phase of ionospheric storms is mainly due to the composition changes (Rishbeth, 1991; Prölss, 1980, 1995, 2011), i.e. the thermosphere becomes richer in molecular nitrogen and poorer in atomic oxygen. The causes of the positive ionospheric storms have also been clarified recently finding that these are the combined effects of disturbed thermospheric wind and electric fields (Tanaka, 1979, 1981; Reddy et al., 1990; Werner et al., 1999; Kelley et al., 2004; Balan et al., 2010). Kelley et al. (2004) suggested that, in the presence of daytime ionization an eastward prompt penetration electric field (PPEF) can strengthen the equatorial plasma fountain to a super plasma fountain, which, in turn, can lead to positive ionospheric storms at midlatitudes. However, modeling studies later showed that a daytime eastward PPEF on its own is unlikely to produce positive ionospheric storms; an equatorward neutral wind is required also to produce positive ionospheric storms (Werner et al., 1999; Lin et al., 2005; Lu et al., 2008; Balan et al., 2009).

Disturbed electric fields are the major source of ionospheric modifications over equatorial and low latitudes. During the development of the storm large polar cap dawn-dusk electric field promptly penetrates to equatorial latitudes (Kelley et al., 1979;

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Fejer and Scherliess, 1998; Kikuchi et al., 1996). The PPEF have eastward polarity during the day- and westward polarity during the night-side of the equatorial ionosphere. The PPEF of eastward polarity can cause large uplift of the ionosphere resulting in large increase of the TEC. During such TEC storms the equatorial ionization anomaly (EIA) can expand poleward with the ionization crests displaced to midlatitudes (Mannucci et al., 2005). It is also well known that the global thermospheric disturbances originating from the auroral heating produce long duration electric fields, known as disturbance dynamo electric fields (DDEF) (Blanc and Richmond, 1980) that dominate the low latitudes with a delay of 4–5 h from the first incidence of the PPEF following the storm onset. These electric fields could last several hours up to one day and have polarity that is nearly opposite to that of the PPEF (Richmond et al., 2003). Therefore, the occurrence of strong daytime eastward and westward electric fields at equatorial latitudes during the main phase of geomagnetic storms seems to be due to PPEF and DDEF, respectively (Batista et al., 1991; Abdu et al., 2006; Fejer et al., 2007).

The positive ionospheric storms observed at subauroral latitudes (Mendillo and Klobuchar, 1975) have been interpreted in terms of the equatorward expansion of the convection electric fields, with no plasma transfer from low latitudes (Foster, 1993; Foster et al., 2002; Foster and Rideout, 2007). Heelis et al. (2009) suggested that the convection electric field at higher latitudes can push plasma to high altitudes where the recombination is much slower, i.e. plasma accumulation occurs. The geomagnetically driven equatorward winds can strengthen the positive storms at subauroral latitudes also (Balan et al., 2011).

It has been already mentioned that the geomagnetic storms dramatically change the ionosphere which affects all branches of telecommunication and navigation and can have significant, adverse effects on ground- and space-based technological systems. Some important terrestrial consequences include possible damage to satellites caused by high energy particles, disrupting UHF satellite communications or detection and tracking of aircrafts, missiles and other targets, increased risk of radiation exposure by humans in space and in high-altitude aircraft, changes in atmospheric drag on satellites. The negative ionospheric storms in which the electron density N_e, peak electron density N_{max} and TEC decrease much below their normal levels may cause serious problems in ground-based HF radio communications. The negative storms therefore received much attention first when the communications were developed mainly on the HF radio waves. The positive ionospheric storms in which N_e, N_{max} and TEC increase much above their normal levels can cause serious problems (such as time delay, range error and scintillations) in satellite communication and navigation. Because the GPS signals are used by wide range of applications, any geomagnetic storm event which makes GPS signal unreliable could have significant impact on the society. Hence the monitoring of ionosphere, particularly during the geomagnetic storms, and modeling and forecasting the evolution of the ionospheric variability are among the important tasks of the ionosphere studies.

Traditionally atmospheric tidal analysis is applied mainly to the dynamics of the neutral middle atmosphere however recently it has been successfully applied to ionospheric parameters as well (Pancheva and Mukhtarov, 2010, 2012). Using this method, ionospheric fields are decomposed in terms of coherent, global-scale oscillations that are sinusoidal in time and longitude. Such tidal analysis of the ionosphere has been utilized primarily for understanding atmosphere - ionosphere coupling through upward propagating tides excited in the lower and middle atmosphere (Pancheva and Mukhtarov, 2010), although in-situ generated ionospheric phenomena have been studied as well in the context of their constituent tidal components (Jones et al., 2013). Recently, the tidal concept with including migrating and non-migrating diurnal oscillations and zonal waves with different wave numbers has been successfully used in constructing a mean empirical TEC model (Mukhtarov et al., 2013a) based on the global ionospheric TEC maps produced by the Center for Orbit Determination in Europe (CODE). Due to this the model is able to reproduce the well-known ionospheric structures such as the Weddell Sea Anomaly (WSA) and some longitudinal wave-like structures as ionospheric wave 3 and wave 4 variations. Recently Chang et al. (2015) have applied tidal decomposition to FORMOSAT-3/COSMIC TEC data to quantify the components dominating local time and spatial variation in the WSA region and found that the features of the WSA can be reconstructed as the result of superposition between the dominant zonally symmetric diurnal (D0), eastward wavenumber 1 (DE1), westward wavenumber 2 (DW2), and stationary planetary wave 1 (SPW1) components in TEC.

The basic goal of the present paper is to make an attempt to clarify the main components dominating local/universal time (LT/UT) and spatial variations in the ionospheric anomalies driven by geomagnetic storms. This will be done by applying tidal decomposition to the geomagnetically forced TEC anomalies, defined from the CODE TEC data, through studying of 4 (four) geomagnetic storms. First the October 29–30, 2003 (Halloween) geomagnetic storms were investigated in detail and then the same approach was applied to the following storms: 7–10 November 2004, 14–15 December 2006 and 5–6 August 2011.

2. TEC data and methodology

The vertical TEC maps generated by the Center for Orbit Determination of Europe (CODE) at Astronomical and Physical Institutes of the University of Bern, Switzerland (http://cmslive3.unibe.ch/unibe/philnat/aiub/content/e15/e59/e126/e440/e447/index_eng.html) are used in this study. The TEC at CODE is modeled with a spherical harmonic expansion up to degree of order 15 referring to a solar-geomagnetic reference frame (Schaer, 1999) and the TEC maps are based on GPS data from more than 200 stations around the globe. The global TEC data have a time resolution of 2 h and a grid spacing of $5^\circ \times 2.5^\circ$ in longitude and latitude, respectively with errors of several TEC Units (TECU, 1 TECU $= 10^{16}$ el/m^2) (Hernández-Pajares et al., 2009). The time resolution of 1 h is used in this study and the hourly data are obtained by interpolation of the 2-hourly original data. More details about the CODE TEC data can be found in Mukhtarov et al. (2013b).

The geomagnetic anomalies are described by the relative deviation of TEC from its sliding median and are denoted as rTEC. Then rTEC $= (\mathrm{TEC_{obs}} - \mathrm{TEC_{med}})/\mathrm{TEC_{med}}$ where the terms $\mathrm{TEC_{obs}}$ and $\mathrm{TEC_{med}}$ represent observed and median TEC values respectively at a given hour. It is important the geomagnetic anomalies presented by rTECs to be able to detect and correctly describe those CODE rTEC anomalies which are generated by geomagnetic disturbances. Such anomalies have usually time scales of a few days up to a week. Due to this a smaller than a month median has to be used. The preliminary examinations revealed that using a 15-day median provides the best opportunity for studying the main features of the TEC anomalies driven by geomagnetic storms. The 15-day window is used also because of the following two reasons: (i) the contribution of the ~27-day rTEC oscillation due to the solar rotation variability of the EUV radiation is significantly weaken, and (ii) such window has an insignificant effect on the 9- and 13.5-day recurrent geomagnetic activity oscillations which are particularly strong during the declining phase of the solar activity (Mukhtarov and Pancheva, 2012).

It is worth underlying that by using rTEC the regular diurnal,