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Association of ionospheric storms and substorms of Global Electron Content with proxy AE index

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Abstract

Storm time modeling of Global Electron Content (GEC) calculated from GIM-TEC for 1999–2013 is associated with new proxy of Auroral Electrojet variability expressed as a smoothed and normalized Auroral Electrojet index (AE_{sn}). The variability in GEC is captured by the computation of DGEC which is obtained by taking the hourly ratio of instant GEC to median of GEC values at the same hour of 7 preceding days. The storm onset is determined by a joint analysis of variations in IMF-B magnitude, its derivative (dB/dt) and direction of IMF-Bz together with sudden increase in AE exceeding 900 nT. The start of the pre-storm period is chosen to be 7 h prior to the storm onset time and the storm recovery period ends 41 h after the storm onset. The hourly AE_{sn} is related to DGEC during the storm period through a polynomial whose coefficients are estimated in the linear least squares sense. Estimated coefficients are examined and grouped with respect to different kinds of auroral storms. Examples of modeling methodology are provided using four different kinds of intense storms and substorms, namely, Positive Arctic, Positive Antarctic, Negative Arctic and Negative Antarctic that occurred between 1999 and 2013. The estimated coefficients for storm periods are compared with those of non-storm periods. It is observed that the positive correlation between the increase of AE and GEC can be a promising precursor of space weather variability.

Keywords: Ionosphere; Global Electron Content (GEC); Total Electron Content (TEC); Auroral Electrojet (AE) index; Space weather; Geomagnetic storms

1. Introduction

Global Electron Content (GEC), which is equal to the total number of electrons in the ionosphere and plasmasphere up to the height of Global Positioning System (GPS) satellite altitude of 20,200 km (Afraimovich et al., 2008), proved itself to be an indicator of global ionospheric storms and substorms that occur due to the coupling of solar wind to earth's magnetosphere and ionosphere rather than redistribution of electron density within ionosphere and plasmasphere shells (Gulyaeva and Veselovsky, 2012). GEC is a complicated function of solar, annual, seasonal, daily and hourly variability of interplanetary space, magnetosphere, plasmasphere and ionosphere. In that sense, it is connected to Auroral Electrojet (AE) index, which is a measure of global electrojet activity in the auroral zone (Davis and Sugiura, 1966; Hajkowicz, 1998; Weygand et al., 2014). The AE index is derived from geomagnetic variations in the horizontal component of the geomagnetic field along the auroral zone in the northern hemisphere. AE index is measured by the magnetometers it represents the currents in the ionosphere at the altitudes

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near 100 km above the Earth, namely AE = AU – AL being a span between the eastward (AU) and westward (AL) electrojects in the ionospheric E-layer. While the physical meaning of AE has been under debate (Kamide and Rostoker, 2004), a relationship between the injection of particles to auroral cusp zones by the geomagnetic storms and reaction due to these activities has been observed in various geomagnetic indices (Liu et al., 2011; Buonsanto, 1999; Gulyaeva and Stanislawska, 2008, Gulyaeva and Stanislawska 2010; Gulyaeva et al., 2014). According to the studies in the literature, when high-speed solar wind interacts with the magnetosphere, the Auroral Electrojet (AE) index increases sharply due to global ionospheric electric fields, which in turn can generate strong internal gravity waves propagating from high to lower latitudes (Hajkowicz, 1999; Deminova et al., 1998; Bowman and Mortimer, 2010).

Ionosphere variability is one of priorities for the past and current investigations due to severe modification of trans-ionospheric signals by highly variable plasma density in space and time, thus affecting the positioning and navigation systems (Schrijver et al., 2015). In this study, the response of GEC to a geomagnetic storm is modeled through a polynomial relationship with respect to the proxy AE index. GEC is included into the model after being modified using a median normalization with respect to the values 7 days prior to the storm day as DGEC. The proxy AE index is smoothed during the storm hours with a sliding window median filter of 7 h. Since DGEC is unitless, smoothed AE is normalized (AE_{sn}) with respect to the largest value within the storm duration (Section 2). The coefficients of the linear relationship are obtained in Least Square (LS) sense. The coefficients of the polynomial model are estimated for all AE storms that occurred between 1999 and 2013.

Examples of DGEC and AE structural model are provided for Positive Arctic (PAr), Positive Antarctic (PAn), Negative Arctic (NAr), and Negative Antarctic (NAn) substorms that occurred between 1999 and 2013. The positive storm is defined with respect to the increase in ionization and electron concentration due to the entry of particles and energy. The measure and distribution of a positive storm is decided with the magnitude of Wp index and W-index which is discussed in Gulyaeva and Stanislawska (2010). For a positive storm, W-index values are +3 and +4 that indicates moderate and severe increase. When the regions with positive disturbance are located in North Polar latitudes, then the storm is designated as a Positive Arctic storm. For the Negative Arctic storms, W-index values are −3 and −4, that indicate a severe depletion in electron density. For Positive and Negative Antarctic storms, W-index values of ±3 and ±4 occur in South Polar Latitudes, in the Southern Auroral zone. The developed method is applied to all AE storms and an example non-storm period. It is observed that quiet ionospheric conditions differ from geomagnetic storms by investigating the coefficients of the event periods. A storm time model can be proposed using the mean and median of the coefficients of polynomial representation for PAr, NAr, PAn, NAn storm types. The methodology for the proposed relationship is provided in Section 3. Results are given in Section 4.

2. Specification of proxy AE index

In this section, the proxy AE index is described. AE index is generally provided with a time resolution of 1 h in the unit of nanoTesla (nT) (http://wdc.kugi.kyoto-u.ac.jp/wdc/). In the investigation of all geomagnetic storms between January 1, 1999 and December 31, 2013, it has been observed that in some disturbances, AE index increases over 900 nT following the increase in IMF and turning of z component of IMF-B (IMF-Bz) to the negative value. In this study, such disturbances are designated as AE storms and included into the analysis. In some geomagnetic storms, the disturbance starts and ends within 48 h or longer. We designated this kind of disturbance as a storm, while substorm is a more fast event lasting 3 to 6 h. In geomagnetic storms that lasts longer than 48 h, there may be cases where the value of AE increases and decreases more than once. Then these kinds of storms are bounded within 48 h durations.

The storm onset time is determined with respect to the increase in IMF-B and the time derivative of IMF-B (dB/dt), along with the turning of IMF-Bz towards negative which are accompanied by the increase of AE either simultaneously or within a few hours. The determination of storm onset time is explained in detail in Section 4. After the storm onset time, the value of AE index increases suddenly but there can be significant small scale variabilities which do not change the trend of increase but can alter the automatic decision of rate of AE increase. In order to avoid the misdetection or wrong decision by the algorithm, we wanted to base our decision of AE increase during a storm period by a smoothed AE value which captures the trend and avoids smaller scale variability. In order to achieve that we have implemented a median filter in a sliding window (swmf) with different window lengths. After the investigation of 92 chosen AE storms, we have decided that a 7 h sliding window length sufficiently encaptures the trend and it gives the minimum least squares percentage error. Therefore, the smoothed trend structure of AE is computed as given in the equation below:

$$AE_{med} = median\{AE(n_h-3),\ldots,AE(n_h),\ldots,AE(n_h+3)\} \quad (1)$$

The smoothed AE values of AE_{med} are normalized within the storm duration N_{st} and smoothed and normalized values are obtained as a proxy $AE_{sn}(n_{st})$:

$$AE_{sn}(n_{st}) = AE_{med}(n_{st})/max(AE_{med}(N_{st})) \quad (2)$$

where $1 \leqslant n_{st} \leqslant N_{st}$, and N_{st} is the storm duration in hours.

In this study, 2240 storms and substorms listed in http://www.izmiran.ru/ionosphere/weather/storm/ from 1999 to 2013 are investigated. These storms/substorms are grouped