Ionosphere response to solar wind high-speed streams

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We present 9- and 7-day periodic oscillations in the global mean Total Electron Content (TEC) from 1 January 2005 to 31 December 2006. Spectral analysis indicates that the pronounced periodicities of 9 and 7 days observed in TEC are associated with variations in solar wind high-speed streams and geomagnetic activity. Neutral temperature and winds near 250 km, measured by a Fabry-Perot Interferometer at Resolute Bay, also exhibit 9- and 7-day periodicities. These pronounced periodicities support simultaneous observations of 9- and 7-day periodicities in thermosphere neutral density (Lei et al., 2008a; Thayer et al., 2008). It is anticipated that the ionospheric response at 9 and 7 days represents some combination of effects due to chemical loss, neutral winds, and disturbance dynamo-driven electric fields. Citation: Lei, J., J. P. Thayer, J. M. Forbes, Q. Wu, C. She, W. Wan, and W. Wang (2008), Ionosphere response to solar wind high-speed streams, Geophys. Res. Lett., 35, L19105, doi:10.1029/2008GL035208.

1. Introduction

Variability in the ionosphere F-region can be caused by solar activity, seasonal and diurnal variations, geomagnetic activity and meteorological influences [e.g., Rishbeth and Mendillo, 2001]. By studying repeatable ionospheric variability on time intervals of days, processes such as meteorological and geomagnetic influences on the F region can be studied in general isolation from the other processes listed above. Of particular attention in recent years is the influence of the lower atmosphere on the F-region [e.g., Altadill and Apostolov, 2003; Mendillo et al., 2002; Forbes et al., 2000]. Tantalizing periodicities observed in the F-region ionosphere of 2, 5, 10, and 16 days have prompted studies invoking lower atmosphere influences due to similar periodicities observed in planetary wave activity [e.g., Altadill and Apostolov, 2003; Laštovička, 2006]. In all these studies, it has been recognized that geomagnetic activity can be a significant contributor to F region variability on time scales of 2–30 days, but little work has been pursued to investigate the solar-terrestrial connection that can cause such variability in the ionosphere and whether the observed multi-day periodicities in the ionosphere may be due to periodicities in solar wind forcing.

2. Data Sets

We use the global mean vertical TEC time series from 1 January 2005 to 31 December 2006. This time series is calculated from global ionospheric TEC maps (GIMs) and corresponds to a time interval where pronounced periodicities of 9 and 7 days were observed in thermosphere neutral density, solar wind velocity and geomagnetic activity [Lei et al., 2008a; Thayer et al., 2008]. The GIMs are provided by Jet Propulsion Laboratory based on the GPS TEC observations from around 200 GPS receivers. The details of the retrieval are given by Mannucci et al. [1998]. The GIMs used here have a longitude and latitude resolution of 5° × 2.5° and temporal resolution of 2 hours. Therefore, there are 72 cells along both the longitude and latitude directions with 5184 total cells in each snapshot of the TEC map. The
Hemisphere are also calculated from equation (1). The main advantage of this method is to mitigate local features in the ionospheric density [Afraimovich et al., 2008].

In addition to the TEC data, the neutral temperature and winds near 250 km from the FPI at Resolute Bay are used to illustrate the pervasive nature of these periodicities in the ionosphere and thermosphere. The information about the FPI at Resolute Bay and the error analysis of the measurements are provided by Wu et al. [2004]. The neutral temperature from days 263 to 321 in 2005 and from days 265 to 366 in 2006, and geographic meridional winds from days 301 to 366 in 2006 are used. The FPI winds in 2005 are not used in this study because of data gaps caused by cloud weather.

The hourly averaged solar wind speed at the L1 point observed by the ACE satellite and the 3-hourly planetary magnetic activity index, Kp, will also be used in this study. The solar wind data are obtained from the GSFC/SPDF OMNIWeb interface and Kp data are provided by NGDC database.

3. Results

Figure 1a shows the variations of the global mean TEC as a function of day number in 2005 and 2006. The annual, semi-annual, and 27-day variations of the global mean TEC are clearly seen in Figure 1a; these variations have been studied by Afraimovich et al. [2008] and Hocke [2008]. Imbedded in the large time scale variations are shorter oscillations with multi-day periods (less than the 27-day solar rotation period). These multi-day oscillations can cause a few units of TEC (TECu) change in the global mean TEC. More significantly, these oscillations were persistent for the entire two year period under study.

To illustrate the characteristics of the periodic oscillations, Lomb-Scargle (LS) periodograms [Lomb, 1976; Scargle, 1982] were calculated on the global mean TEC in 2005 and 2006 (Figure 1b). Dominant spectral components above the 95% significance level in the 2005 data set, in order of highest to lowest amplitudes, are found at periods of 27, 9 and 13.5 days with amplitudes of 1.3, 0.4 and 0.3 TECu. In the 2006 data set, periods of 27, 7 and 9 days are predominant with the amplitudes of 0.7, 0.23 and 0.2 TECu (we refer to oscillations with periods from 22 to 32 days as the 27-day oscillation). From the LS periodograms, we can see that the amplitudes of the 7-, 9-, and 13.5-day oscillations are around one third of the 27-day oscillation. Hocke [2008] also found the 7-, 9-, and 27-day oscillations from a spectral analysis using global mean TEC from January 1995 to March 2007, and showed a perfect correlation in the 27-day oscillation between global mean TEC and solar EUV. However, Hocke suggested other mechanisms rather than solar irradiation should contribute to the 7-, and 9-day oscillations in global mean TEC because the 9-day periodicity is absent in the Mg II spectrum and 7-day oscillation of solar EUV is negligible. Note that the spectral analysis for the solar EUV radiation flux from the SEM/SOHO during 2005–2006 also indicates that solar radiation variations are too small [Lei et al., 2008b] to explain the observed 7- and 9-day variations in TEC.

Now we focus on the investigation of whether the 7- and 9-day periodicities in TEC correspond well with recur-
rent geomagnetic activity and periodic high speed solar wind streams. Note that the 13.5-day periodicity will not be studied here, although this component is present in the TEC spectrum in 2005. This is because the 13.5-day periodicity can be present in both solar EUV radiation and geomagnetic activity [e.g., Mursula and Zieger, 1996]. A comparison of LS periodograms of percent residual TEC from 11-day running mean (obtained from N−5.5 to N+5.5 days, where N is the current day) with those of solar wind velocity and geomagnetic activity index Kp in 2005 and 2006 is also shown in Figures 1c–1g. Here we use the mean TEC at high, middle and low latitude bands instead of the global mean TEC in order to examine the latitudinal dependence of the 7- and 9-day periodicities in TEC. It is evident that the 7- and 9-day periodicities in TEC are similar to the oscillations in solar wind and Kp. All variables (i.e., TEC, solar wind and Kp) have a dominant peak at 9 days in 2005, and pronounced peaks at 7- and 9-day periods in 2006. The relative amplitudes in TEC, with 3–4% for the periodicities at the periods of 9 days in 2005 and 7 days in 2006, can be observed at all latitudes, with some indication of greater change at high latitudes than at low latitudes. The relative fluctuations are about ±6% if a band-pass filter with a width of 2 days, centered on 9 days or 7 days, is applied due to the nonsinusoidal nature of theses periodicities. Hocke [2008] showed that the relative amplitude for the 27-day periodicity is about 8–14% during 2005–2006 [see Hocke, 2008, Figure 6]. Although the 7- and 9-day periodicities in TEC are smaller than 27-day periodicity, they still can introduce significant day-to-day variations in the ionospheric density because of their much higher occurrence frequency, which will be discussed later.

Figure 2. Evolution of the wavelet power spectra of percent residual from (top) 11-day running global mean TEC, (middle) solar wind velocity, and (bottom) Kp in (left) 2005 and (right) 2006. The white solid contours denote the regions of the wavelet spectrum above 95% confidence level, and the horizontal white dashed lines indicate the positions of the periods of 5, 7, 9, and 13 days. Highest intensities are in red and lowest in dark blue.

4. Discussion and Conclusions

We have presented the 9- and 7-day periodic oscillations in the global mean TEC during 2005–2006. The relative fluctuations in the 9- and 7-day periodicities in TEC are about ±6% and introduce significant recurring variations in the ionospheric electron density. Our spectral analysis reveals that the pronounced periodicities of 9 and 7 days observed in TEC are associated with the variations of solar wind stream and geomagnetic activity. The remaining question is why the periodicities of solar wind and geomagnetic activity cause periodic ionospheric oscillations at 9 days or 7 days.

Lei et al. [2008a] and Thayer et al. [2008] reported the pronounced periodicities of 9 and 7 days observed in the CHAMP neutral densities in 2005, and 2006, respectively. The neutral mass density measured by the CHAMP satellite is primarily responding to temperature changes in the thermosphere that lead to a redistribution of mass density. Although this type of mass redistribution is not necessary to affect the relative concentrations of atomic and molecular
species, there remains an impact on the ionosphere, through changes in its peak height influenced by neutral temperature for example [e.g., Zhang et al., 1999].

[13] Figure 3 shows the neutral temperature spectra in the winter seasons (when the northern polar cap was in nighttime condition) of 2005 (Figure 3, top) and 2006 (Figure 3, middle) measured by the Resolute Bay FPI instrument. In 2005, the 9-day periodicity is clearly seen in the neutral temperature with an amplitude as large as 60 K. In 2006, the spectral amplitude at 6–7 days is most distinct, with less pronounced peaks at 9, 4, and 13 days. It is evident that the spectra of temperature are also similar to those of solar wind and Kp in Figure 1. The temperature periodicities are expected to affect the electron density in the F2 region or TEC by changing the recombination rate and the F2 layer height of the ionosphere.

[14] The O/N2 ratio may exhibit similar oscillatory behavior linked to recurrent geomagnetic activity as mass density and neutral temperature. Daytime O+ densities up to the F2 peak are strongly influenced by the ionization of O and its chemical loss [e.g., Prölls, 1995]. It is lost by chemical reactions, primarily with N2 and O2. As a result, the O+ density is often related to changes in the O/N2 ratio during the day and time integrated changes in 1/N2 density at night. Thus the periodicities in neutral composition caused by the recurrent geomagnetic activity may play an important role in the periodicities of electron density in F2 region or TEC.

[15] In addition, the F region electron density or TEC can be significantly changed by transport through neutral winds and electric fields [e.g., Prölls, 1995]. The variations of Joule and particle heating at high latitudes due to the recurrent geomagnetic activity may force neutral winds to oscillate at the periods of 7 and 9 days. As shown in Figure 3, the 6–7 day oscillation above 95% confidence level is clearly seen in the Resolute Bay FPI meridional winds in 2006, although the 6–7 day oscillation is not as pronounced as in the neutral temperature and there is also a broad spectrum of the wind periodicities in the range of 2–7 days. This may be related to less reliable wind data due to cloud weather. It must be recognized that observations at this location may not be representative of global or even regional conditions. On the other hand, electric fields are generated by neutral winds in the E region in daytime and in the F region at night, or they penetrate from magnetosphere to ionosphere. The penetration electric fields from magnetosphere can not last multi-days because of the shielding of the region 2 current, whereas electric fields may oscillate at the same frequencies as neutral winds through the disturbance wind dynamo process [Blanc and Richmond, 1980]. Thus, the 7-, and 9-day periodicities in electric fields or neutral winds modulated by the solar wind and geomagnetic activity are also potential causes for the corresponding periodicities in electron density and TEC.

[16] Mlynczak et al. [2008] reported a 9-day periodicity in the infrared cooling of the mesosphere, and also suggested a direct coupling between the Sun’s upper atmosphere and the infrared energy budget of the lower thermosphere. It is interesting that the periodic fast solar wind streams and recurrent geomagnetic activity even affect the lower thermosphere. The excited lower thermosphere by the recurrent geomagnetic activity may play a role in producing the periodicities in electron density and TEC in complex and coupled pathways. Due to the impact on the lower thermosphere, it is interesting to note that studies using mesosphere/lower thermosphere winds to extract planetary wave periodicities, such as by Altadill and Apostolov [2003], may be contaminated by the recurrent periodicities in geomagnetic activity. This can further confuse the relation of planetary wave periodicities to correlations in F-region variability.

[17] An extensive and impressive review of TEC contributions to ionospheric storms is given by Mendillo [2006]. Our findings further enhance the utility of TEC measurements for ionosphere study. However, the processes at play in modifying the ionosphere require additional data sources and model simulations to understand the relative contribution of the periodicities of the neutral density, neutral temperature, neutral winds, neutral composition and electric fields associated with periodic high speed solar wind streams and recurrent geomagnetic activity in driving the ionospheric periodic oscillations. We expect these multi-day periodicities to be observed in other thermosphere/ionosphere/magnetosphere data sets in solar minimum thus enabling a much more extensive analysis of the entire geospace response to solar wind high speed stream disturbances.

Figure 3. Lomb-Scargle periodograms of neutral temperature in (top) 2005 and (middle) 2006 and (bottom) meridional winds in 2006 measured by the Resolute Bay FPI in the winter seasons. The dashed lines represent the 95% significance level.
References


