Response of Low-Latitude Ionosphere to Medium-Term Changes of Solar and Geomagnetic Activity

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[1] The paper presents the medium-term quasi periodic (~9–27 day) response of middle and low-latitude ionosphere to solar [F10.7] and geomagnetic (Kp-index) forcing. The ionospheric response is examined by wavelet analysis of the relative deviations of TEC over Japan for the period of time 2000–2008. It is found that the ~27-day rTEC oscillations correlate well with the same oscillations of the solar index F10.7 particularly in the solar maximum and its early declining phase (2001–2005). During the declining phase of solar activity (for example, year of 2005) the Kp-index variability exhibits additionally strong oscillations with periods 13.5- and 9-days. Similar oscillations are found in rTEC as well but they do not follow the geomagnetic forcing as faithfully as those associated with F10.7. During solar minimum the quasi periodic rTEC variability is shaped mainly by the recurrent geomagnetic activity. An attempt is made to investigate the latitudinal dependence of the ~9–27-day rTEC response over Japan as well as the phase relationship between the forcing and response.


1. Introduction

[2] Quasi-27-day periodicity is a typical medium-term response of the ionosphere to changes in solar and geomagnetic activity. The main factor generating such changes is the repeatable influence of active regions on the Sun’s surface which rotates with a period of 27 days. This influence is transmitted to the Earth in two ways: by EUV radiation and by the solar wind. It is well accepted that the neutral atmosphere and ionosphere respond collectively to both these solar influences, but the time scales of their responses are still uncertain. The 27-day periodicity in the solar EUV radiation directly impacts the ion production. Since the pioneering works of Maunder [1904] and Bartels [1934] numerous papers were devoted to the solar 27-day periodicity and its effects on the upper atmosphere and ionosphere. Recently, the presence of a 27-day oscillation in the ionosphere has been reported by Altadill et al. [2001], Altadill and Apostolov [2003], and Pancheva et al. [2002]. Pancheva et al. [1991] however revealed that very frequently this oscillation, observed in the lower ionosphere (D-region), can be from direct solar origin during high solar activity and of meteorological origin (i.e., disturbances from the lower atmosphere) during low solar activity. The latter has a period between 22 and 28 days, and is observed mainly in winter and at the equinoxes. Later Luo et al. [2001] and Pancheva and Mitchell [2004] found that the planetary waves (PWs) in the mesosphere-lower thermosphere (MLT) with periods ~23–25 days are regularly observed during winter and equinoxes. The authors showed also that these are vertically upward propagating waves that are correlated with the solar rotation period. Usually the long-period ~23–25 days PWs in the MLT show some delay of several days with respect to the solar rotation oscillation seen in the solar F10.7 radio flux [Pancheva and Mitchell, 2004]. This means that both the MLT and ionospheric oscillations may be associated with the 27-day solar activity rather than the ionospheric oscillations are caused by the MLT waves.

[3] Solar 10.7 cm radio flux (F10.7) is commonly used as a proxy for the solar EUV radiation affecting the Earth’s atmosphere. Rich et al. [2003], based on data from DMSP spacecraft from subauroral latitudes, have suggested that 27-day variations in plasma density are mostly topside phenomena, while the simultaneously measured total electron content (TEC) at this latitudes does not show such periodicity. Their results, however, may not be valid for the mid- and low-latitude ionosphere. Min et al. [2009] studied the 27-day modulation of the low-latitude ionosphere during solar maximum by using data from KOMPSAT-1 and DMSP satellites. They also revealed a clear periodic variation with period around 27 days in the topside ionosphere. By removing 30-day averages from the data, the authors found a good correlation between the TEC and F10.7. A first
estimation of the solar-forced ionospheric quasi-oscillations in total electron content (TEC) was achieved by Borries and Hoffmann [2010] using wavelet filter algorithms. They ascribed 38–42% of the planetary wave type oscillations [with periods between 2 and 30 days] observed in TEC to quasiperiodic variability in the EUV, solar wind speed and geomagnetic disturbances.

[4] Solar wind high speed streams (HSSs) emanating from solar coronal holes cause recurrent, moderate geomagnetic activity, which can last more than one solar rotation [see, for example the review of Tsurutani et al. [2006a] and therefore induce 27-day variations in the ionosphere. HSSs, when emanating away from the Sun, interact with preceding low-speed solar wind and form a “co-rotating interactive region (CIR).” This interface region between low- and high speed solar plasma produces geomagnetic disturbances when it interacts with the Earth’s magnetosphere. Thus, a single coronal hole can produce multiple CIRs if the hole lives longer than one solar rotation. Both, HSSs and CIRs generate moderate geomagnetic storms and continuous auroral activity. Tsurutani et al. [2006b] have studied the response of daytime ionosphere to these co-rotating HSSs. They found a small effect of these recurrent storms on the mid- and low-latitude ionosphere, except for a short period of time when IMF Bz turns sharply negative at the time of initial contact of the CIRs with the magnetosphere. During these short periods, a daytime eastward electric field penetrating into the equatorial ionosphere, produces and an enhanced upward E × B drift. Lei et al. [2008a] studied the 9- and 7-day periodic oscillations in the global mean TEC derived from ionospheric TEC maps (GIMs) for the period 2005–2006. They found that the pronounced periodicities of 9- and 7-days observed in the mean TEC are associated with variations in solar wind high-speed streams (HSS) and geomagnetic activity. These authors suggested 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.

[5] Modifications of the midlatitude F region during persistent HSSs have been studied by Denton et al. [2009]. By using superposed epoch analysis, these authors studied changes in F region parameters before and after the onset of magnetospheric convection, the latter represented by sudden increases of Kp index above 4. They found that nighttime peak density decreases consistently with storm onset and gradually recover to the pre-storm levels in about 4 days. The daytime peak density also exhibits a sharp increase at storm onset, followed by a decrease below the quiet level that again gradually recovers within 3–4 days.

[6] Temmer et al. [2007] compared the variability of coronal holes areas with solar wind data and geomagnetic indices for January–September 2005. Applying wavelet analysis, they found a clear 9-day periodicity in both coronal hole appearance and solar wind parameters. These authors suggested that these periodic variations are caused by coronal holes distributed roughly 120° apart in solar longitude. This topology was stable between 10 January and 20 June 2005, followed by a dual coronal holes distribution producing 13.5-day periodic variations up to the end of the observation period. Coronal holes are most prevalent during the declining phase of the solar cycle and can persist for many solar rotations [Borovsky and Denton, 2006; Vršnak et al., 2007].

[7] Recurrent geomagnetic activity is also associated with periodic heating of the atmosphere and subsequent periodic neutral wind changes. As a result of the periodic temperature and wind perturbations, a global thermospheric density response can be expected. Recently the 9-day variability has been found in the neutral density of the Earth’s thermosphere [Lei et al., 2008b] and the infrared energy budget of the thermosphere [Mlynczak et al., 2008]. Thayer et al. [2008] have shown that the thermospheric mass density response is global and varies coherently with the recurrent geomagnetic activity, although the response is slightly larger at high latitudes. Crowley et al. [2008] have also reported 9-day periodic oscillations in the $\Sigma$O/N$_2$ ratio measured by the Global Ultraviolet Imager (GUVI) on the TIMED satellite. The authors showed that the $\Sigma$O/N$_2$ ratio response is opposite at high and low latitudes due to upwelling and downwelling of the atmosphere.

[8] The global thermospheric changes, associated with recurrent geomagnetic activity, modify the plasma neutral interactions. Hence, the recurrent geomagnetic activity leads to changes in ionospheric electron density and TEC. Recently, oscillations at periods of 7 and 9 days during 2005 and 2006 in global mean GPS TEC were correlated with recurrent solar wind HSSs, related to coronal holes distributed on the Sun [Lei et al., 2008a; Pedatella et al., 2010; Mukhtarov et al., 2010]. More recently, Tulasi Ram et al. [2010a, 2010b], Zhang et al. [2010], Liu et al. [2010], and Mukhtarov and Pancheva [2012] have used global electron density profiles from satellite measurements to investigate the ionospheric response to recurrent geomagnetic activity at different latitudes and altitudes.

[9] In this paper we study a medium-term periodic (9–27 days) response of mid- and low-latitude ionosphere represented by relative deviations of TEC over Japan during the period 2000 through 2008. The main goal is to clarify which of the both forcing mechanisms: solar or recurrent geomagnetic has a prevailing effect on the low-middle latitude TEC response during the solar cycle. Using wavelet analysis, we demonstrate that oscillations with periods around 27 days comprise the main periodicity of the ionosphere during most of the considered period of time. The amplitude of these oscillations is highly correlated with solar F10.7 radio flux. During the declining phase of solar activity, 13.5- and 9-day oscillations are also present in Kp, but the TEC reaction to these oscillations is not always adequate. Geomagnetic activity disrupts the more regular 27-day variation, producing negative and positive deviations, but the ionosphere recovers within a few days to reveal the basic 27-day variation. We discuss the possible causes of the observed phenomena.

2. Data

[10] The ionospheric response to medium-term solar and geomagnetic forcing is characterized by the GPS-derived TEC obtained from Japanese GEONET GPS network. In the paper, we follow the same data manipulation scheme as that described by Kutiev et al. [2005, 2007]. For each hour numerous individual TEC measurements were averaged.
within cells of $1.5^\circ \times 1.5^\circ$ in latitude and longitude. For the present analysis, the database was enlarged to cover hourly TEC data for the years 2000–2008. Figure 1 shows the location of the average TEC values over Japan ($24^\circ–45^\circ$N and $124^\circ–145^\circ$E) at 00 UT on 1 February 2000. For each location, hourly medians are calculated for a 27-day time window and assigned to the 15th day of the window. The window is successively moved by one day to cover the entire period under study. Then, the relative deviations of hourly TEC values from their respective 27-day medians are obtained for each location. However, the relative deviations were calculated separately for each year and therefore first and last 14 days of the years are missing. For statistical analysis, the hourly average TEC deviations in each cell are fitted with two regression lines, representing a lower latitude band ($24^\circ–29^\circ$N) and an upper latitude band ($29^\circ–45^\circ$N) in the region of Japan. In this way the TEC variability over the Japan area at any hour are represented by 4 parameters: the mean TEC values (denoted as $r_{\text{TEC}}$) in the middle of the southern and northern subranges at $27^\circ$ and $39^\circ$ respectively and the corresponding slopes of the regression lines. As seen in Figure 1, both regression lines are tilted $45^\circ$ to the east. To assure a relatively equal number of TEC values for the fitting, we restricted the area to $\pm 6^\circ$ from the central line, where enough TEC data are always available. Further in the paper we denote the mean $r_{\text{TEC}}$ of regressions as $r_{\text{TEC}27}$ for southern and $r_{\text{TEC}38}$ for northern subranges.

[11] For better visualization, summary plots of $r_{\text{TEC}27}$ and $r_{\text{TEC}38}$ are produced for 3-month intervals, along with corresponding geomagnetic indices. A sample of such a plot is shown in Figure 2 for days 15–90 of year 2002. The upper portion shows corresponding variations of $K_{p}$ (gray bars), $A_{E}$ (magenta line), and $D_{st}$ (blue line), as the $A_{E}$ and $D_{st}$ scales are given on the right. The period shown in Figure 2 is in the maximum of solar activity; geomagnetic activity is high, although intense storms did not occur. $r_{\text{TEC}27}$ and $r_{\text{TEC}38}$ show large day-to-day variability, but on the medium time scale they exhibit a well expressed 27-days variation. This is well seen between day 40 and day 90. In further analysis we will show that a 27-day oscillation dominates over much larger time periods, but is frequently disrupted by geomagnetic storm forcing. Also important are the two harmonics: producing 13.5 and 9 days oscillations, which presumably also have solar origin. Kutiev et al. [2005] have pointed out that the relative deviations of TEC from medians obtained in 27-day windows express well the oscillations of this basic period and its harmonics. Indeed, if we consider a pure 27-day periodic variation, for each hour the number of values with positive and negative amplitudes are equal, e.g., the median is zero. Thus the total amplitude of the periodic variation is seen in the relative TEC variation. This is also true for 27-day harmonics, with periods of 13.5 and 9 days. For periods which differ from these exact durations, the median will not be exactly zero and will reflect part of the underlying variation. However, this property of the relative deviations from 27-days medians can assist in the description of solar activity induced variations at low and midlatitudes. Bearing in mind that geomagnetic latitude at Japan longitudes is $9^\circ$ less than geographic latitude, $r_{\text{TEC}27}$ and $r_{\text{TEC}38}$ are representative of the ionosphere in geomagnetic latitude bands between $15^\circ–20^\circ$ and $20^\circ–36^\circ$ respectively.

[12] It is seen that rTEC exhibits large oscillations with period of 2 days and less. Although the medians remove

**Figure 1.** Location of the average TEC values over Japan ($24^\circ–45^\circ$N and $124^\circ–145^\circ$E) at 00 UT on 1 February 2000.
most of the diurnal variation, the amplitudes of $r$TEC27 and $r$TEC38 over these shorter periods show large day-to-day variability. Often the variations in each subregion have the opposite phase, which suggests that the ionosphere in near the equatorial anomaly crest and the midlatitude ionosphere are controlled by different processes. In this paper we will not consider these shorter term variations, but will concentrate on variations, having time scales of 5–6 days and more, which we call medium-term variations.

[13] In this analysis we examine the power spectra of ionospheric quantities, presented in the form of amplitude wavelet spectra. The $r$TEC oscillations with periods 5–30 days are transient phenomena that are most effectively identified by a wavelet transform method. The wavelet analysis presented here employs the continuous Morlet wavelet, which consists of a cosine wave modulated by a Gaussian envelope. The non-dimensional frequency, which gives the number of oscillations within the wavelet itself, is set to six to satisfy the wavelet admissibility condition [Torrence and Compo, 1998]. The Morlet wavelet was selected because of its simplicity and convenience in investigating wave-like events observed in the atmosphere-ionosphere system [Pancheva and Mukhtarov, 2000]. The localization characteristics in time and frequency space of the Morlet wavelet used in this study are as follows: the time localization, or the so-called “cone of influence,” is defined as a time interval which contributes to the wavelet coefficient at a given instant $t_o$. In our case the influence cone is: $t \in [t_o - \sqrt{2a}, t_o + \sqrt{2a}]$ where $a$ is the wavelet scale and 1.03 $a = T$, where $T$ is the Fourier period. Likewise, the localization characteristics of the wavelet in frequency space give local information about the function in the frequency range: $\omega \in \left[\frac{1}{2} + \frac{1}{2\sqrt{2}}; \frac{1}{2} + \frac{1}{\sqrt{2}} \right]$. The frequency resolution can be increased by using a wavelet with intrinsic frequency higher than 6, albeit at the expense of decreased time resolution.

[14] As an example, Figure 3 shows wavelet spectra (WS) for the indices Dst, Kp and F10.7 for the year 2002. The period ranges between 3 and 30 days. Amplitudes are color coded and their magnitude is given on the right. Both Dst and Kp exhibit strong oscillations between DoY 60–130 and 230–320 with a dominant period around 25 days. Smaller amplitudes with periods around 13.5 and 9 days can also be distinguished. Kp variations with period of 5–6 days are connected with geomagnetic storms.

[15] It is clear that variations in the solar index F10.7 and the geomagnetic indices both have dominant periods near 25 days that are related to the solar rotation period. However, the epoch during the year, at which the influences of periodic variations in the solar EUV irradiance and geomagnetic activity are seen, occur at different time. Variations in F10.7 with period centered at 24 days exhibit a large maximum between DoY 190–250 and a second increase after DoY 350 while the influence of recurring geomagnetic storms are centered near day 105 and day 270. Figure 4 represents the wavelet spectra of $r$TEC27, $r$TEC38, and the integrated rTEC over the whole latitude range (rTECtotal) for the same year 2002. The spectra of the three quantities are quite similar exhibiting a large maximum with a period of 23–28 days between day 120 and day 320. Figure 4 shows also a ~9-day rTEC response near days 80–120 and 230–280; while the first response is entirely shaped by the Kp-index the second one is a combination of solar and geomagnetic effects with some prevalence of F10.7. In order to facilitate the comparison of the rTEC response to solar and geomagnetic forcing the color scales of both, rTEC27 and rTEC38, quantities are the same. It becomes clear that the amplitudes have practically the same magnitudes with those of rTEC27 being, in general, a bit larger. The maximum of rTEC38 amplitudes appears around day 270 and its position resembles that of Kp, but the rTEC27 also shows large amplitudes around these days and its amplitude is even larger than that of the rTEC38. This means that the ~27-day rTEC response in 2002 is complex one with a clear contribution of the F10.7 and Kp-index which impact maximizes around days 210 and 270 respectively. It should be noted that the wavelets of rTEC and connected with them Kp and Dst values begin on 14th and end on 351th day, due to the way of calculating medians separately for each year.
Figure 5a shows the magnitude of 27-days oscillation in both rTEC27 [red line] and rTEC38 (green line) for the whole period of analysis 2000–2008. The magnitude of the 27-day oscillation in F10.7 is also shown with the scale on the right. The magnitudes of the 27-day periodicities in F10.7 are significantly higher in the period of 2000–2005 than those in 2006–2008. During the first period, covering the solar maximum and subsequent declining phase, the 27-day periodicities in rTEC are also the largest and quite well correlate with those in F10.7 except in 2000 and in the first half of 2003. Therefore, the 27-day periodicities in rTEC seen in the period of time 2001–2005 are generated predominantly by the respective oscillations in F10.7. In general, a weak prevalence of the 27-day rTEC27 response than that in rTEC38 can be distinguished. In the period of 2006–2008 the 27-day periodicities in F10.7 are extremely small. The same periodicities in rTEC are smaller than those seen in the previous years but still with not negligible magnitudes. This is an indication for the predominant effect of the 27-day variability in the geomagnetic activity or possibly of long-term (20–30-day) PWs forced from the lower atmosphere on the ~27-day oscillations seen in the rTEC during 2000 and 2006–2008. As discussed later, F10.7 may be not suitable to describe the solar activity during 2007–2009.

In order to investigate any periodicities simultaneously present in two or more time series a refinement of the wavelet analysis is used usually. In this particular case, we apply a cross-wavelet analysis, where the cross-wavelet power serves as an indication for the strength of the oscillations co-existing in both time series, and the argument describes the instantaneous phase difference between them. The cross-wavelet power result is not shown here as it is very similar to the observed good correlation between 27-day amplitudes in F10.7 and in rTEC27 and rTEC38 in the period of 2001–2005 shown in Figure 5a. Figure 5b shows the phase difference in radians between 27-day oscillations of rTEC27 (red line) and rTEC38 (green line) and those in F10.7. It is seen that between 2001 and 2005 the phase difference is slightly positive when there is simultaneous enhancement of the 27-day oscillations in F10.7 and in
rTEC27 and rTEC38. On the average the phase difference changes between 0 and 0.5 radians, i.e., between 0 and around 2 days. This means that the 27-day oscillations in rTEC 27 or rTEC 38 experience some delay than those in F10.7. Figure 5b displays predominantly negative phase difference in 2000 and 2006–2008. This can be interpreted as an opposite ionospheric response to the forcing or a delay of the ionospheric response larger than 13.5 days. It has been already mentioned that the ~27-day oscillations observed in the lower ionosphere during low solar activity are usually of meteorological origin [Pancheva et al., 1991], hence the 27-day rTEC oscillations in 2006–2008 could be forced from below. Some contribution of the 27-day Kp-index variability however cannot be excluded. The latter is supported by the analysis of the ionospheric parameter foF2 obtained from the global COSMIC electron density profiles for the period of time October 2007–March 2009 (P. Mukhtarov, private communication, 2012). This analysis showed ~27-day response of the COSMIC parameter foF2 to the same recurrent geomagnetic activity during the end of 2007 and first half of 2008. Additionally it revealed also that the amplitudes of the 27-day oscillations in foF2 maximize near ±20° modip latitudes. As the TEC is to large extent determined by the electron density of the F2 layer maximum and because the rTEC27 response is closer to 20°N modip latitude than that of rTEC38 that is why on the average the ~27-day oscillations in rTEC27 due to recurrent geomagnetic activity are stronger than those in rTEC38 (2000 and 2006–2008). It is worth mentioning also that the phase difference between the 27-day oscillations in COSMIC foF2 and Kp-index for latitudes of Japan also showed small negative values (P. Mukhtarov, private communication, 2012). This could be due to the complex influence of the geomagnetic disturbances on the ionosphere through changes of the neutral density, temperatures, dynamics, chemistry and an enhanced upward E × B drift. It is worth noting also that the confidence level of the obtained phase difference strongly

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**Figure 4.** Wavelet spectra of rTEC27, rTEC38, and the integrated rTEC over the whole latitude range (rTECtotal) for the same year 2002.
depends on the magnitude of the oscillations; it significantly decreases with decreasing of the amplitudes.

[18] Figure 6 combines the medium-term WS plots of F10.7, Kp, rTEC27, and rTEC38 for the year 2003. rTEC in both sub-regions show well defined oscillations with period around 25–28 days throughout the whole year. But most significant are 2 maxima in the amplitude of the variation, representing departures from median levels by more than 30% that coincide with the same F10.7 periodicities centered near day 90 and day 290. Kp variations are rather typical of geomagnetic activity during a period of high solar activity. They show no coherent reproducible periodicity except near the end of the year when a periodicity near 25 days begins to emerge. Oscillations of Kp with periods near 13 and 7 days appear sporadically throughout the year representing the occurrence of recurrent geomagnetic storms that might also affect the rTEC. However, the rTEC variability does not seem to follow Kp variations, neither at 27-day, nor at 13.5- and 7-day periodicity. The increase of rTEC amplitude between days 200 and 270 is not visually connected with solar and geomagnetic activity. The rTEC27 and rTEC38 topology [in period/time frame] is very similar and does not suggest for any latitude dependence.

[19] Figure 7 shows the same variations as those described in Figure 6, but for the year 2005. Again, the maxima in rTEC27 with period near 25–27 days coincide well with similar maxima in F10.7; even the observed 27- and 25-day periods seen in F10.7 near day number 40 and 190 are reproduced in the rTEC. The Kp variations with such period show only very weak maxima around day 20 and day 260 that are not well reproduced in rTEC. The impressive feature in the Kp spectra is the well defined oscillation around period of 9 days. Its amplitude is significant during the whole year. There is some rTEC response but it is seen only around days 20–60 and 240–260 (rTEC38 shows response also around days 300–350). The examination of the rTEC variability and that in the geomagnetic activity described by the AE and Dst indices (not shown in the figure) shows some decrease after day 280. There is not a significant latitudinal difference between rTEC27 and rTEC38 responses to the 9-day recurrent geomagnetic activity, except that the rTEC27 response is larger than that of rTEC38 in the first three months of the year.

[20] The year 2005 belongs to the declining phase of solar activity, when the magnetic activity produced by high-speed solar wind streams (HSS) and associated Co-rotating Interaction Regions (CIRs) prevail over the storms induced by Coronal Mass Ejection (CME) events [see, e.g., Tsurutani et al., 2006a, and references therein]. It is known that HSS and CIR storms are produced by the high speed solar plasma...
emerging from coronal holes on the Sun, when the latter expand from the polar region toward the solar equator. As far as Kp is a measure of geomagnetic forcing on the ionosphere, CIR and HSS storms can transfer the topology of coronal holes on the rotating solar surface, into corresponding oscillations in the Kp index and ionospheric parameters [Lei et al., 2008a; Liu et al., 2010]. Figure 8 shows the amplitudes of Kp variations with periods of 27, 13.5, and 9 days. It is clearly seen that the amplitudes of the 13.5- (blue line) and 9-day (green line) oscillations exceed those of 27-days oscillations (red line) during most of the time between 2000 and 2008. The 9-day oscillation has an amplitude maximum in late 2004 and throughout 2005. The 13.5-day oscillation has a maximum one year earlier.

The wavelet spectra in Figure 7 indicate that during 2005 the rTEC27 does not generally follow the 9-day oscillations seen in the Kp variation, except near days 40 and 240. The panels of Figure 9 show the amplitudes of 27-day (top), 13.5-day (middle), and 9-day oscillations seen in the rTEC27 (magenta) and the Kp-index (green) for the whole 9-year period. In the top panel, the amplitude of F107 (orange), the same as in Figure 5a, is shown for reference. The amplitudes of Kp and F107 clearly show their contributions in the combined forcing to the rTEC27 response. We find out that only at specific periods, marked by horizontal red bars, the peaks in the 27-day variations of the rTEC27 and Kp are aligned. Prior to solar maximum, in 2000, the largest variations in the rTEC27 arise with 27 day period at times that coincide with 27-day periodicities in the Kp-index indicating a driver that is dominated by geomagnetic activity. Throughout the solar maximum period, 2001–2003, the simultaneous 27-day periodicities in the rTEC27 and Kp are quite rarely observed. This is consistent with the more random nature of solar eruptions leading to geomagnetic activity during this period. Indeed the largest amplitude variations in Kp are seen with 9-day periodicities that are more likely to capture the typical duration of large magnetic storms. The 9-day periodicities in rTEC27 are quite small during this period and largely uncorrelated to those in Kp. This suggests that the response of the midlatitude ionosphere to geomagnetic activity occurs on time-scales and with phase delays that differ from the drivers. During the end of

Figure 6. Medium-term WS plots of F10.7, Kp, rTEC27 with the summary plot of the type of Figure 2 for the year 2003.
Figure 7. The same variations as those described in Figure 6, but for the year 2005.

Amplitudes of Kp oscillations

Figure 8. Amplitudes of Kp variations with periods of 27, 13.5 and 9 days.
solar maximum and in the declining phase of the solar cycle, from 2003 to 2005, the 27-day variations in rTEC27 are the largest observed in the entire 9-year period and are almost uncorrelated with magnetic activity, indicating that the dominant driver for these periodicities during this interval is the solar ionizing flux. The only exception is seen in the last quarter of 2003 when a large peak of Kp amplitude takes place, most probably connected with the intense geomagnetic storm on 29–30 October (Halloween storm). The variations in the Kp index with 13.5-day and 9-day periodicities are retained throughout this interval with the magnitude and extent of the 9-day variations increasing. There are notable alignments between 9-day variations in the Kp and the rTEC27 that exist in 2005 during the periods of strong 27-day variations in rTEC27. These are indicated by red arrows in the figure. During the solar minimum period, 2006–2008, the amplitude of 27-day periodicities in Kp and rTEC27 become smaller than those seen previously, while the 9-day variations in Kp and rTEC27 become much better correlated. This suggests that a transition to recurrent geomagnetic activity variations is taken place and that the ionosphere responds more coherently to these quasiperiodic drivers.

A good example of coherent 9-day oscillations in the Kp-index and rTEC27 is seen in 2008, marked by blue arrows and bar in the bottom plot of Figure 9. In order to examine the detailed relationship between both oscillations again a cross wavelet analysis is applied. The upper plot of Figure 10 shows the instantaneous amplitudes of the 9-day oscillations of the Kp-index (green) and those of the rTEC27 (magenta) in 2008 while the bottom panel displays the phase difference (in radians) between them. The best coincidence between both oscillations can be distinguished around day numbers 60, 165, 215 and between days 270–330. In all cases the phase difference is close to zero or positive but less than 1–1.2 radians, i.e., less than ~1.5 days. This means that the 9-day oscillations generated in the rTEC27 by a 9-day recurrent geomagnetic activity in Kp-index usually experience some delay than the forcing. A similar time-lag result was obtained by investigating the COSMIC middle and low latitude foF2 ionospheric response to the 9-day recurrent geomagnetic activity in 2008 [Mukhtarov and Pancheva, 2012]. Such similarity between the rTEC and foF2 response can be expected in advance because the TEC variability depends mainly on the electron density at the F2 maximum.

During the declining phase of the solar cycle the basic medium-term variations of rTEC have periods of 20–30 days. They account for most of the total (daily averaged) deviations of the rTEC. Their amplitudes closely follow the variations of the solar index F10.7. It is apparent that the geomagnetic storms disrupt the underlying variation of rTEC and give rise to shorter term changes, which appear in WS plots as intensification of shorter period oscillations. The ionosphere responds to the geomagnetic forcing and recovers to the underlying longer period variation within 3–5 days, depending on the intensity of the storm. Figure 11 illustrates this behavior. A periodic variation, with period close to 27 days is superimposed as the solid black curve on rTEC variations shown between day 180 and day 270, in 2004 (top panel). This curve is not drawn to exactly represent the underlying large-scale variation but rather to provide a reference from which the small scale deviations can be easily identified. The vertical arrows mark the start of some of these deviations, which coincide with the beginning of the storms. At the onset of a large storm (DoY 202), the rTEC drops from its positive deviation of 0.2 down to a value of −0.2. As a result of the three storms, the rTEC recovers from −0.5 on DoY 210 to −0.1 at DoY 212 which is close to the
underlying base level. The periodic line is interrupted between DoY 210 and 219 in order to better fit the baseline in the following rTEC variations. Two weak storms on days 210 and 221 invoke a positive deviation of rTEC, while another weak storm on DoY 230 causes a large negative deviation, changing the rTEC from 0.4 to \(-0.3\) within two days. Then from day 231 rTEC starts to recover, reaching the underlying base level of 0.2 on day 238. Similar changes of the rTEC occur during the storm starting on DoY 253, when the rTEC recovers from day 259 to day 262. 

From Figure 11 we find that the underlying variation in the rTEC has close to a 27-day period; the geomagnetic storms disrupt it with both positive and negative rTEC variations that return to the underlying baseline in 1–3 days. These assumptions were checked over the whole database. In many cases recoveries are interrupted by new storms.

Figure 10. (top) Amplitude of 9-day oscillations seen in Kp-index (green line) and rTEC27 (purple line) observed in 2008. (bottom) Phase difference (in radians) between the 9-day oscillations in Kp-index and rTEC27.

Figure 11. The rTEC variations between days 180 and 270, in 2004, superimposed by a periodic variation (solid black curve), with period close to 27 days. Vertical arrows mark the start of some of these deviations, which coincide with the storms onsets.
which make the statistical analysis difficult. During some periods in Figure 11, when the storms appear isolated from each other, the above behavior is readily seen. Two important features can be extracted from the visual inspection of the data. The first is that the sign of the disruption in the basic variation of rTEC depends on the phase of the variation. When rTEC is positive, disruption is toward negative values. When disruption appears during declining rTEC, then the disruption is positive. The second feature is that the amplitude of the disruption is not proportional to the strength of the storm (measured by Kp or Dst).

[25] Here we summarize the main observational features described above.

[26] 1. Daily variations in TEC [rTEC] oscillate with periods between 20 and 30 days. The amplitude of this oscillation is almost equal to the daily average total deviation of rTEC.

[27] 2. Oscillations of rTEC with periods near 27 days correlate well with the same oscillation of solar index F10.7. They are less coherent with those of Dst and Kp, particularly during the period of time 2001–2005. In general, the ∼27-day rTEC27 response is slightly larger than that of rTEC27 regardless of its origin solar or geomagnetic (Figure 5a).

[28] 3. When there is simultaneous enhancement of the 27-day oscillations in F10.7 and in rTEC27 and rTEC38, particularly well seen between 2001 and 2005, then the phase difference is slightly positive; on the average it changes between 0 and ∼2 days (Figure 5b). This means that the 27-day oscillations in rTEC 27 or rTEC 38 experience some delay than those in F10.7.

[29] 4. During the declining phase of solar activity (year 2005), Kp, being a measure of geomagnetic forcing on ionosphere, exhibits strong oscillations with periods 13.5- and 9-days. Significant oscillations in rTEC in Japan latitudes sometimes coincide with this forcing but the variations are not followed as faithfully as those associated with F10.7. A clear correlation between the 9-day oscillations in Kp and those in rTEC 27 is found during 2008 (Figure 9, bottom plot). The phase difference between the simultaneous enhancement of the 9-day oscillations in rTEC 27 and Kp was found to be close to zero or positive but less than ∼1.5 days (Figure 10).

[30] 5. The variation of rTEC with period around 27 days is disrupted by geomagnetic storms. The ionospheric response depends on the phase of the basic variation: while TEC is positive, changes are negative and vice versa (Figure 11).

[31] 6. The recovery phase of ionospheric storms brings the ionospheric state to the level of the underlying 27-day variation in 1–3 days (Figure 11).

3. Discussion

[32] In this paper we have presented the quasi periodical ionospheric TEC response over Japan to ∼9–27-day oscillations with solar (F10.7) and geomagnetic (Kp or Dst) origin. The examination of the relative daily deviations in TEC from a 27-day running median most clearly identifies variations with this period and its harmonics. Such variations are shown in this analysis and have also been identified by Min et al. [2009] using a similar technique. In order to clarify which of the both forcing solar or recurrent geomagnetic has a prevailing effect on the low-middle latitude TEC response during the solar cycle a 9-year period of time (2000–2008) is considered.

[33] The amplitude of 27-day variation of rTEC correlates very well with the same variation of F10.7 particularly during solar maximum and in its declining phase (2001–2005). In general the 27-day rTEC27 response is larger than that of rTEC38. The phase difference between the F10.7 forcing and the ionospheric rTEC response is on the average between 0 and 2 days indicating that that the 27-day oscillations in rTEC experience some delay than those in F10.7. As far as F10.7 is a proxy of the solar EUV intensity, it is clear that the direct photochemistry contributes significantly to the medium-term variations of ionosphere. However, we note that particularly during the declining phase and the minimum of solar activity the correlations between the magnitude of rTEC variations and F10.7 variations suggests that indirect effects, perhaps produced by the recurrent geomagnetic activity or PWs with a period close to 27 days, described by Luo et al. [2001] and Pancheva and Mitchell [2004], could also have contributions. Additionally, it is known that the PWs modulated tides can transfer the PW variability from the lower to upper atmosphere and then to affect the ionosphere [Pancheva et al., 2002]. The thermospheric tidal fields are larger at sunspot minimum than at sunspot maximum [Hong and Lindzen, 1976] due to a lower neutral density and a smaller ion drag. Thus during the declining phase and solar minimum conditions the ∼27-day TEC response could be due to different sources.

[34] Min et al. [2009] have correlated the 27-day amplitudes of 30-day filtered TEC and neutral density obtained by CHAMP accelerometer data with that of F10.7. They found that 27-day amplitudes of both quantities are highly correlated with that of the F10.7 index with the maximum response delayed by one day. Increased neutral density in periods of amplitude maximum, combined with increased EUV ionizing radiation lead to increased ion production that follows a 27-day variation.

[35] As it is seen from Figure 5a, the correlation between the 27-day amplitudes of rTEC and F10.7 worsen at low solar activity. Chen et al. [2011] showed that during the years 2007–2009 the F10.7 index does not represent adequately the solar EUV intensity being lower than that in the previous solar minimum. Solomon et al. [2010] showed that, while during the last solar minimum F10.7 was less by 5% compared with previous solar minimum, the EUV intensity was lower by 15%. Therefore, for the same level of F10.7, the EUV intensity differs significantly in the last two solar minima. Rich et al. [2003] compared different solar indices as proxies for the solar ionizing radiation and found that the F10.7 performs better than SOLAR2000 [Tobiska et al., 2000] and SUSIM [Woods et al., 1996]. Maruyama [2010], however, studied the TEC response to solar activity changes and found that the Mg II core-to-wing ratio (M10.7) and the integrated 26–34 nm emission by SOHO SEM [S10.7] indices were better proxies of the EUV emission than the F10.7 index. The latter fact might contribute to the worsened correlation between the rTEC and F10.7 amplitudes. Indeed, the peak amplitudes of the rTEC27 in 2006 decrease 1.8 times (on average) compared with those in 2005, while in 2007 and 2008 these ratios, compared to 2005, are 2 and 3 respectively. The F10.7 amplitude ratio compared to 2005 is 2.5 in 2006, 4 in 2007 and 6 in 2008. Therefore, the peak
amplitude of F10.7 decays two times faster than that of rTEC as solar activity approaches its minimum. Another reason for the slower decay of the rTEC peak amplitude, compared with that of F10.7, can be found in the increased significance of the effect of HSS and CIR storms as well as in the possible forcing from below by modulated tides with periods of the extra long-period PWs that have solar origin.

36 During the solar maximum period coherent medium scale periodicities of 13.5 and 9 days in the Kp index are quite weak and that rTEC is not well correlated to them when erratically appear. In 2005, when the 9-day amplitude of Kp is highest in the examined period, the simultaneous peaks of rTEC amplitude seen in the first and third quarter of the year [marked with red arrows] are more probably connected with those of F10.7. However, during the solar minimum period in 2008, both Kp and rTEC amplitudes with 13.5 and 9 day periods are more coherent, representing the recurrent geomagnetic storms with period of 9 days that are known to exist at this time. Therefore, we can conclude that during this period, the ionospheric response to Kp forcing dominates than that from the solar EUV radiation.

37 Figures 4, 6 and 7 allow comparing the amplitudes of rTEC27 and rTEC38 in order to check for a latitudinal dependent response to CIR periodicity. We inspected all rTEC WS plots in the database for possible latitude dependence. The result revealed a slight prevalence of the rTEC27 amplitudes than those of rTEC38. The 9- and 27-day rTEC responses are in accordance with the obtained latitude structure of the 9- and 27-day foF2 periodicities seen in the COSMIC electron density measurements (Mukhtarov and Pancheva [2012] for 9-day and P. Mukhtarov (private communication, 2012) for 27-day forF2 variability) which show a clear amplitude enhancement near 20°N modip latitude. The 13.5-day rTEC response does not show clear latitudinal dependence. In general, we can state that the recurrent geomagnetic storms affect almost equally rTEC27 and rTEC38, with the amplitude of rTEC27 being a bit larger.

38 The 27-, 13.5- and 9-day recurrent geomagnetic activity affects the TEC, but the main effect appears inside individual storms, when large positive and negative deviations from the average state may occur. These deviations however have a time scale less than 3 days (the lowest period in our analysis). The response of rTEC to 13.5- and 9-day oscillations of Kp are rear as it is clearly seen in WS plots. There is a solar cycle dependence of the degree of this response. Figure 9 illustrates clearly this fact. In the top panel, horizontal red bars indicate the time period when peaks of Kp amplitude are aligned with those of rTEC and we consider that contribution of Kp, or recurrent geomagnetic activity, dominates over that of F10.7. In Figure 9 (bottom), the red arrows indicate the position of amplitude peaks, when both Kp and rTEC27 are aligned. In the year 2008, the peaks exhibit remarkable alignment, which indicates that at very low solar activity, the main driver of the 9-day periodicity of TEC is the recurrent geomagnetic activity. The detailed examination of the phase relationship reveal less than 1.5-day delay of the ionospheric response with respect to the geomagnetic activity forcing. A similar time-lag result was obtained by Mukhtarov and Pancheva [2012] through investigating the COSMIC middle and low latitude foF2 ionospheric response to the 9-day recurrent geomagnetic activity in 2008.

39 As it was mentioned above, the paper deals with longer-term periodicity, not with disturbances produced during storms. The impact of the recurrent geomagnetic activity on the ionosphere in the context of the paper should be read as how the ionosphere reacts to a series of repeatable (recurrent) geomagnetic storms with periodicity of 9 or 13.5 days. The shorter-term positive and negative disturbances during storms obviously disrupt longer-term variations driven by the onsets of the storms. We can speculate that such longer-term periodicities appear in WS when the storm appearance is less frequent and/or disturbances are not so large to disrupt those oscillations. This really happens, because the recurrent geomagnetic storms are less intensive than the CME storms.

40 The response of the rTEC shown here and its relation to the 27-day variations produced by the solar ionizing flux, clearly requires further investigation over the time scales of a few days. Denton et al. [2009] studied statistically the reaction of the F-layer parameters to HSS storms. They found that when the storm onset happens during the day, the peak density increases on the first day, decreases on the second and then slowly recovers to its quiet state during the next 3–4 days. For storm onsets at night, the peak density decreases on the first day and then recovers similar to the previous case. This result complies with the common understanding of the development of ionospheric storms at mid- and low-latitudes. Stormtime behavior of rTEC during initial and main phases of geomagnetic storms is usually more complex than in the described scheme above. It will be necessary to discover the relative magnitudes of storm time negative and positive phases and their dependence on the changes in F10.7 in order to reconcile the apparent dependence seen in this analysis.

4. Conclusion

41 Examination of the time series of TEC variations at low-midlatitudes over Japan illustrates the changing influence of the solar ionizing flux and of the magnetospheric disturbances on the ionosphere.

42 1. During solar maximum and early declining phase a dominant 27-day variation in the TEC is clearly linked to the same variations in the solar ionizing flux as represented by F10.7. During solar maximum a coherent periodic response to magnetic activity is not seen in TEC, except in 2000 when the 27-day rTEC response is almost entirely of geomagnetic origin.

43 2. As the solar activity declines the periodic nature of the forcing by CIR’s emerges in the time series of Kp and TEC.

44 3. The background variations of rTEC with period around 27 days are disrupted by geomagnetic storms. The recovery phase of ionospheric storms brings the ionospheric state to the level of the underlying 27-day variation in 1–3 days.

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