Quasi 10-day wave modulation of equatorial ionization anomaly during the Southern Hemisphere stratospheric warming of 2002

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Abstract

The present paper studies the perturbations in equatorial ionization anomaly (EIA) region during the Southern Hemisphere (SH) sudden stratospheric warming (SSW) of 2002, using the location of EIA crests derived from Global Positioning System (GPS) station observations, the Total Electron Content (TEC) obtained by International GNSS Service (IGS) global ionospheric TEC map (GIMs), and the equatorial electrojet (EEJ) estimated by geomagnetic field in Asian sector. A strong quasi 10-day periodic oscillation is clearly identified in northern and southern EIA region. This quasi 10-day oscillation is also seen in the polar stratospheric temperature and EEJ, suggesting the enhanced quasi-10-day planetary wave associated with SSW produced oscillation in EIA region through modulating the equatorial fountain effect. Our results reveal some newer features of ionospheric variation that have not been reported during Northern Hemisphere (SH) SSWs.

1. Introduction

Sudden stratospheric warming (SSW) is large-scale meteorological process in the polar stratosphere which is characterized by rapid rise in temperatures and deceleration/reversal in the zonal mean flows (Scherhag, 1952). The primary driver of SSW is thought to be a rapid growth of quasi-stationary planetary wave interacting with zonal mean flow (Matsuno, 1971). Although the main processes of SSW occur in the middle atmosphere, its effects on the ionosphere have been observed in significant changes of equatorial electrojet (EEJ), vertical plasma drift, and equatorial ionization anomaly (EIA) (Vineeth et al., 2007; Chau et al., 2009; Goncharenko et al., 2010; Pancheva and Mukhtarov, 2011; Jin et al., 2012). These ionospheric variations mainly display similar semidiurnal pattern and 13- to 16-day wave signatures which have been associated with planetary wave, solar and lunar tide wave (Pedatella and Forbes, 2009; Goncharenko et al., 2010; Fejer et al., 2010; Park et al., 2012). Since stationary planetary waves in the Southern Hemisphere (SH) generally have smaller amplitudes than in the Northern Hemisphere (NH) where orographic and thermal forcing is stronger (Andrews et al., 1987), major SSWs often occur in NH. Therefore, most studies about SSW effects on the ionosphere are during NH SSW period.

In August to September 2002, three minor SSWs and a major SSW appeared in SH (Varotsos 2002; Baldwin et al., 2003). There is sufficient evidence that a series of unusual atmospheric states occurred in this period, i.e., planetary wave scale quasi 10-day variation (Krüger et al., 2005; Palo et al., 2005), short-term semidiurnal tide variability with zonal wave number s=1 (Chang et al., 2009) and the winds oscillation with ~14-days period (Andrew et al., 2004), are all linked to the extremely large planetary wave events. Although the atmospheric activity in connection with 2002 SH SSW has been well revealed in observations and numerical modeling, relatively little is known about the ionosphere effects of 2002 SH SSW. Recently, Olson et al. (2013) studied the equatorial electrodynamic perturbations in Peruvian sector during 2002 SH SSW and found enhanced quasi 2-day fluctuations and large amplitude multi-day perturbations in EEJ and vertical drifts. The researches of ionospheric behavior during SH SSW periods are useful for verifying the existing explanation about the origin of ionospheric perturbations during NH SSW periods and revealing some newer features of ionospheric variation, so further investigation of 2002 SH SSW effect on ionosphere with more ionospheric parameters is still warranted.

In the present study, we present the first observational evidence of quasi 10-day oscillation in EIA region during 2002 SH SSW which has not been reported during NH SSWs, based on the location of EIA crests derived from Global Positioning System (GPS) station observations, the Total Electron Content

(TEC) obtained by International GNSS Service (IGS) global ionospheric TEC map (GIMs), and the EEJ estimated by geomagnetic field in Asian sector.

2. Data and Methods

The location of EIA crests derived from GPS observations are used to analyze the variation in EIA region during 2002 SH SSW from July 20, 2002 to October 27, 2002. The GPS stations are GUAN (23.19°N, 113.34°E, MLAT~12.52°N) and BAKO (6.49°S, 106.84°E, MLAT~17.18°S) which are near northern and southern EIA crest, respectively. The locations of the GPS stations are shown in Figures 1. Since the ionospheric vertical TEC usually reach the maximum at EIA crest, the location of EIA crest can be obtained by vertical TEC values at each ionospheric penetration point (IPP), which is the intersection of the line of sight and the ionospheric shell (assumed to be 400 km) (Mo et al., 2014). The relative accuracy of the TEC is 0.02 total electron content unit (1TECU=10^{16} el m^{-2}) (Hofmann-Wellenhof et al., 1992). The sample rate of these GPS stations were 30s, so the resolution of the location of EIA crest is less than 25 km (Mo et al., 2017). Figures 2a and 2b show the daily average geomagnetic latitude (MLAT) of northern and southern EIA crests during 2002 SH SSW.

The TEC from GIMs are also used to analyze the variation in EIA region. The GIMs provides maps of TEC obtained from a global network of GPS receivers, which have temporal resolution of 2 hours and spatial resolution of 5° in longitude and 2.5° in latitude (Mannucci et al., 1998). The EIA crest usually reaches its maximum development near 14:00 LT (Huang et al., 1989; Yeh et al., 2001), so the daily average TEC obtained by GIMs at 12~14 LT, ±5º~±15º MLAT, 100º~150ºE every day in Asian sector are used to describe the variation in northern and southern EIA region, the results are shown in Figures 2c and 2d.

To demonstrate the dynamical process in EIA region, the EEJ is also used in this study, which can be estimated by the difference between the horizontal component of geomagnetic field at TIR (8.7°N, 77.8°E, MLAT~0.03°N) and VSK (17.68°N, 83.32°E, MLAT~8.56°N) (Rastogi et al., 1990). The results are shown in Figures 2e. In addition, the polar stratospheric temperature (90°S, 10hPa) and zonal mean zonal winds (60°S, 10hPa) obtained from National Centers for Environment Prediction (NCEP) are used to examine the extent of the SSW, the results are shown in Figures 2f and 2g. The background of geomagnetic activity index (Kp) and solar flux index (F10.7) from the websites http://spidr.ngdc.noaa.gov/ are depicted in Figures 2h and 2i.

3. Results and Analysis

It can be seen from Figures 2f and 2g that there were three obvious minor SH SSW events around day number 230-260 and a major SH SSW event around day number 263-288 (Olson et al., 2013). Figure 3 shows the contour map of polar stratospheric temperature (80°S, 10hPa) obtained from NCEP from July 20, 2002 to October 27, 2002. An eastward phase progression of quasi 10-day wave is clearly observed around day number 210-270. With SABER temperature data, Palo et al. (2005) also observed similar disturbance and suggested it consists of an eastward-propagating quasi 10-day wave with zonal wave numbers s=1 superimposed upon a large stationary planetary wave with s=1.

Now we examine the impact of this quasi 10-day wave on EIA region. It should be noted the solar/magnetospheric forcing on ionosphere are strong due to 2002 SH SSW event occurring during solar maximum year. To exclude these long period fluctuations in EIA region associated with solar/magnetosphere forcing, the periods longer than 15 days in the MLAT location and TEC of EIA crest, and EEJ are removed. Specifically, these parameters are subtracted from their respective 15-day moving average. The residuals are subjected to Lomb-Scargle (L-S) spectral analysis (Lomb,1976; Scargle, 1982), and the results are shown in Figures 4a, 4b, 4c, 4d, and 4e. The horizontal dashed lines represent the 95% confidence level. It is evident that the MLAT location and TEC of EIA crest, and EEJ all exhibit significant quasi 10-day periodic component, which exceed or approach 95% confidence level, suggesting that the whole dynamical process in EIA region is modulated by quasi 10-day wave. Figures 4f and 4g show the L-S spectral analysis of Kp and F10.7. It can be seen that spectral component of Kp also has quasi 10-day periodic component which will be related to solar wind high-speed streams (Lei et al., 2008). However, this quasi 10-day periodic component is too weak to be identified in F10.7, indicating that variation in the solar flux cannot account for this quasi 10-day oscillation in EIA region.

To investigate the time evolution of quasi 10-day periodic variation, the Morlet wavelet spectral analysis is applied to MLAT location and TEC of EIA crest, EEJ and Kp which exhibit quasi 10-day oscillation. The periods longer than 15 days in the MLAT location and TEC of EIA crest , and EEJ are removed before the wavelet spectra is generated, and the results are illustrated in Figures 5a, 5b, 5c, 5d, and 5e. The black solid contours in each panel indicate a significance level higher than 95%. The white line in each panel represents the cone of influence of the wavelet analysis. The color bar number is the power strength for each parameter. Obviously, the most predominant periodic component in the MLAT location and TEC of EIA crest, and EEJ are quasi 10-day period, which mainly appeared around day number

210-290, indicating quasi 10-day oscillations in EIA region go through three minor SSWs and a major SSW period. The time evolution of the power in MLAT location and TEC of northern EIA crest match well those of southern EIA crest, respectively. In addition, we note both the MLAT location and the TEC of EIA crest show the quasi 2-day oscillations during major SSW period (around day number 260-270), which are also found on equatorial ionospheric electric fields and currents at the same period (Olson et al., 2013). Figure 5f shows the wavelet spectral analysis of Kp index. It can be seen that quasi 10-day periodic component is nearly absent in Kp around day number 230-290, suggesting that magnetic activity should not be the driving force for this quasi 10-day oscillation in EIA region.

In order to demonstrate the phase relationship of the quasi 10-day oscillations between northern and southern EIA crests, the band-pass filter is performed on the MLAT location and TEC of EIA crest. The absolute values of the MLAT location of EIA crest are used. The band-pass filter is centered at the period of 10-day, with half-power points at 8-day and 12-day, and the results are shown in Figure 6. The quasi 10-day wave amplitudes of northern and southern EIA crests are roughly equivalent, which exceed 1.7 degree for MLAT location and 7 TECU for TEC, respectively. Although the quasi 10-day wave of northern EIA crest match well those of southern EIA crest, the wave of northern EIA crest seemed to delay behind southern EIA crest, especially for MLAT location. To further verify this, Figure 7 shows the cross-correlation of quasi 10-day waves in MLAT location (a) and TEC (b) between northern and southern EIA crests. The cross-correlation coefficients of MLAT location and TEC reach 0.8 and 0.93, respectively. Moreover, the maximum cross-correlation coefficients for MLAT location is at 1 day, indicating that the wave of northern EIA crest delay 1 day behind southern EIA crest. This phase difference between northern and southern EIA crests may be due to differences in longitude between two GPS stations.

4. Discussions

In recent years a series of reports have focused on ionospheric perturbations during SSW event. The most predominant features in ionosphere associated with SSW event are semidiurnal pattern and 13- to 16-day wave variations, which are attributed to nonlinear interaction of planetary wave, solar and lunar tide wave (Pedatella and Forbes, 2009;Goncharenko et al., 2010; Fejer et al., 2010;Park et al., 2012). As major SSW often occurs in NH, most studies about SSW effects on the ionosphere are during NH SSW period. In August to September 2002, the first major SSW was observed in SH. The NH and SH SSW occurred in Arctic and Antarctic winter, respectively, so the occurring time and location of SH SSW are opposite to those of NH SSW. The researches of ionospheric behavior during SH SSW periods are useful for testing the general rule of ionospheric perturbations during NH SSW periods. For example, Olson et al. (2013) demonstrated that multi-day ionospheric perturbations responding to 2002 SH SSW resemble those observed during NH SSWs and these ionospheric perturbations were associated with enhanced lunar tidal effects.

In the current study we present observations of quasi 10-day oscillation in EIA region during the 2002 SH SSW that have not been reported during NH SSWs. This quasi 10-day oscillation is absent and weak in Kp and F10.7 index, indicating that the magnetic activity and solar flux cannot account for this quasi 10-day oscillation in EIA region. Meanwhile, an unusual atmospheric state occurred in this period that the ozone hole over the Antarctic has a smaller size and splits into two separate holes (Varotsos 2002; Baldwin et al., 2003). This phenomenon is thought to be due to high temperatures the Antarctic, which was contributed to by upward propagation of a planetary wave (Venkat Ratnam et al., 2004). Moreover, strong planetary wave scale quasi 10-day variation was observed in polar stratospheric temperature during this period (Krüger et al., 2005; Palo et al., 2005), so the quasi 10-day oscillations in EIA region may be related to atmosphere perturbations linking the SSW in the Southern Hemisphere.

A series of studies have showed how the quasi 10-day planetary wave in stratosphere can penetrate into the ionosphere E region. Krüger et al. (2005) revealed the eastward-traveling waves with periods near 10 days and their interaction with quasi-stationary planetary waves forced in the troposphere during 2002 SH SSW event, supporting the observational and numerical evidence that the eastward traveling wave interacts with the stationary wave to produce a quasi-periodic amplitude modulation of the stationary waves (Hirota et al., 1990; Ushimaru and Tanaka, 1992). Palo et al. (2005) found an eastward-propagating quasi 10-day wave with zonal wave numbers s=1 and s=2, and a quasi-stationary planetary waves with s=1 extend from the lower stratosphere to the 100-120 km height region with little amplitude attenuation. While the quasi-stationary planetary wave is confined to the high latitude atmosphere and cannot directly propagate to equatorial ionosphere, the tides were introduced into planetary wave modulation mechanism. Eswaraiah et al. (2018) reported that zonal diurnal and semidiurnal tide amplitudes in Antarctica mesosphere and lower thermosphere were enhanced around day number 230-290 during 2002 SH SSW, which coincides with the enhanced period of quasi 10-day oscillations in EIA region shown in Figure 5. Moreover, Chang et al. (2009) showed that the short-term variability of the s=1 semidiurnal tide is strongly dependent upon the PW1 events (quasi-10-day wave) prior to the major warming during 2002 SH SSW, supporting the suggestion that the quasi-stationary planetary wave can influence migrating and nonmigrating solar tides globally (Liu et al., 2010; Pedatella and Forbes, 2010). So the interactions between quasi-10-day planetary wave and tide will modify the ionosphere E-region winds, which can produce E-region electric fields via the E-region dynamo process. In this study, the evidence of quasi 10-day periodic variation of EIA crests and EEJ strongly supports the suggestion that quasi-10-day planetary wave produced oscillation in EIA region through modulating E-region electric fields. Specifically, the E-region electric fields map to F-region along the magnetic field lines and generate an eastward electric field (Goncharenko, 2010). At the magnetic equator, the eastward electric field with quasi 10-day periodic variation change electron density distribution in the low-latitude region via $\vec{E}\times\vec{B}$ drift, and finally leads to quasi 10-day planetary waves characteristic variations in EIA region. The effects of planetary wave on the equatorial fountain effect have been revealed by the evidence that the vertical and latitudinal structures of the 6-day oscillation in the F region ionosphere peak on both sides of the equator in the EIA region (Gu et al., 2014). The synchronous 10-day oscillation between northern and southern EIA crest in our results are consistent with these observations.

In our prior studies, a 14- to 15-day wave during several NH SSW events is ascribed to lunar tide (Mo et al., 2018). So the source of quasi 10-day oscillations in EIA region during 2002 SH SSW is different from 14- to 15-day waves during NH SSW. Moreover, no obvious 14- to 15-day oscillation is found in EIA region during 2002 SH SSW, which may be that the equatorial lunar semidiurnal effects during September-October are weaker than that during January-February (Stening et al., 2011; Pedatella, 2014). Olson et al. (2013) also reported that the perturbations amplitude of EEJ and vertical drifts modulated by lunar semidiurnal tides during SH SSW are smaller than those during NH SSW.

5. Conclusions

Using the location and TEC of EIA crests derived from GPS station observations and GIMs, we found a quasi 10-day periodic variability in northern and southern EIA region in Asian sector during the SH SSW of 2002. In the same time period, this quasi 10-day oscillation is also seen in the polar stratospheric temperature and EEJ, which is absent and weak in Kp and F10.7 index, respectively. Previous studies have shown that a strong quasi 10-day planetary wave with zonal wave numbers s=1 extend from the lower stratosphere to mesosphere and lower thermosphere (Palo et al., 2005), so the quasi 10-day variation in EIA region should be ascribed to enhanced 10-day planetary wave in lower atmosphere associated with SSW.

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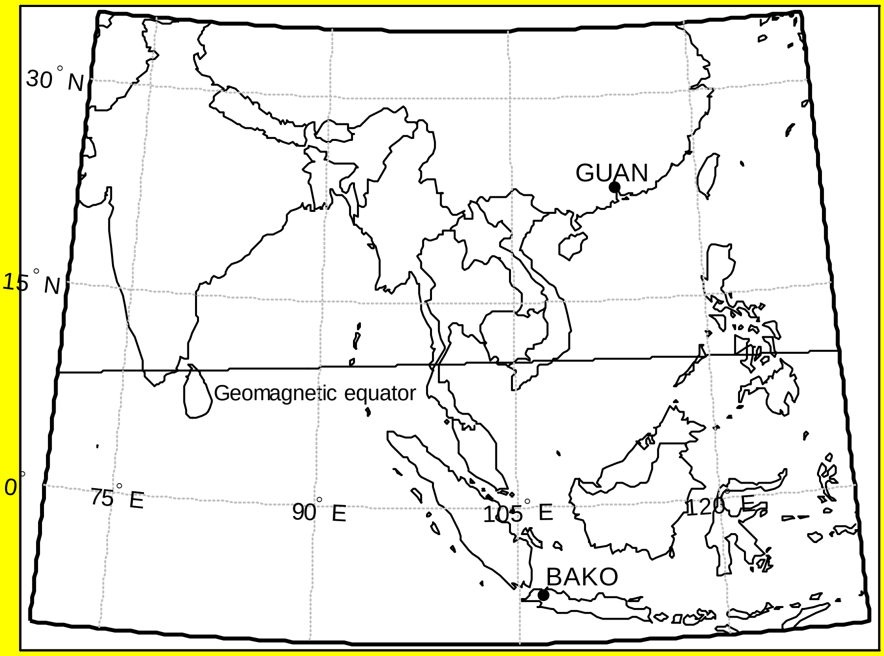


Figure 1. Location of the GPS stations in Asian sector.

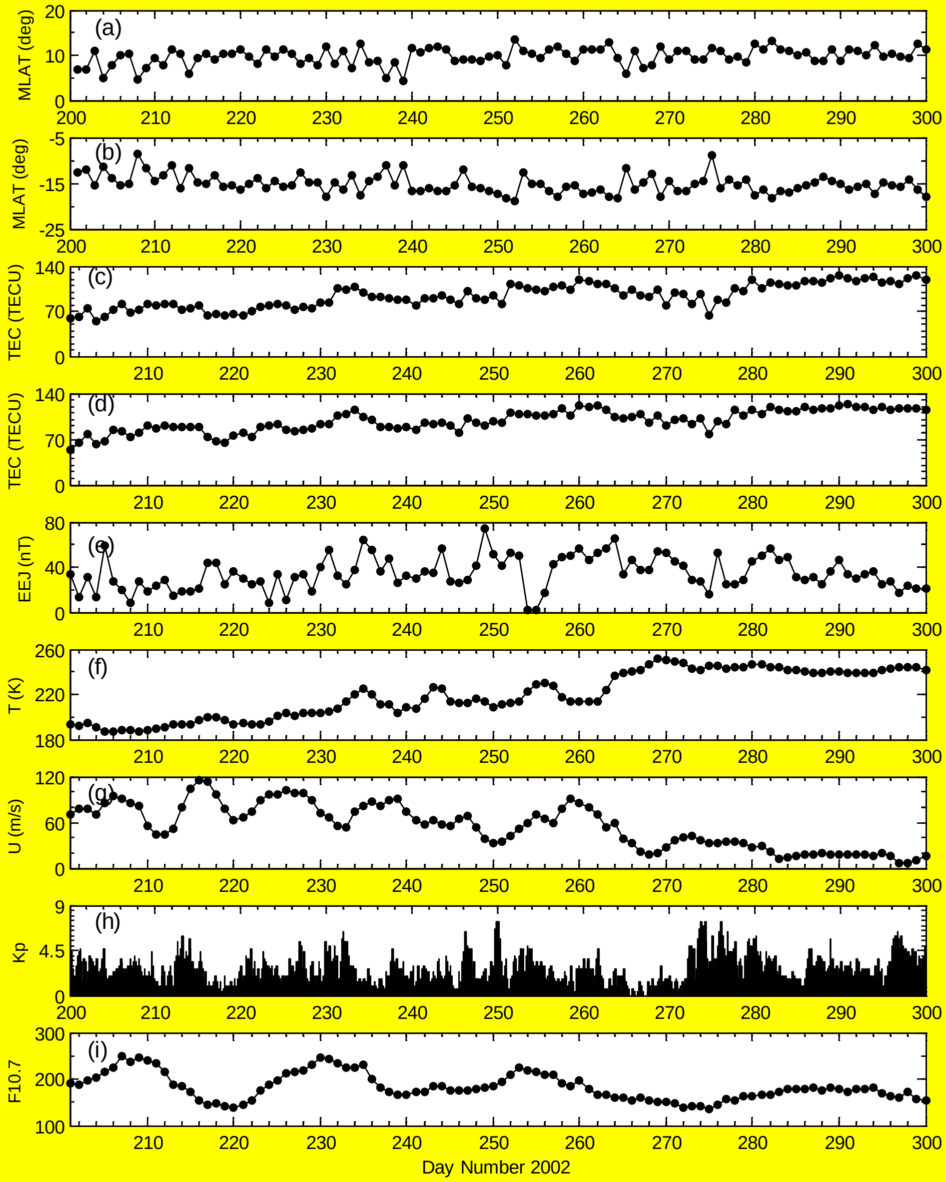
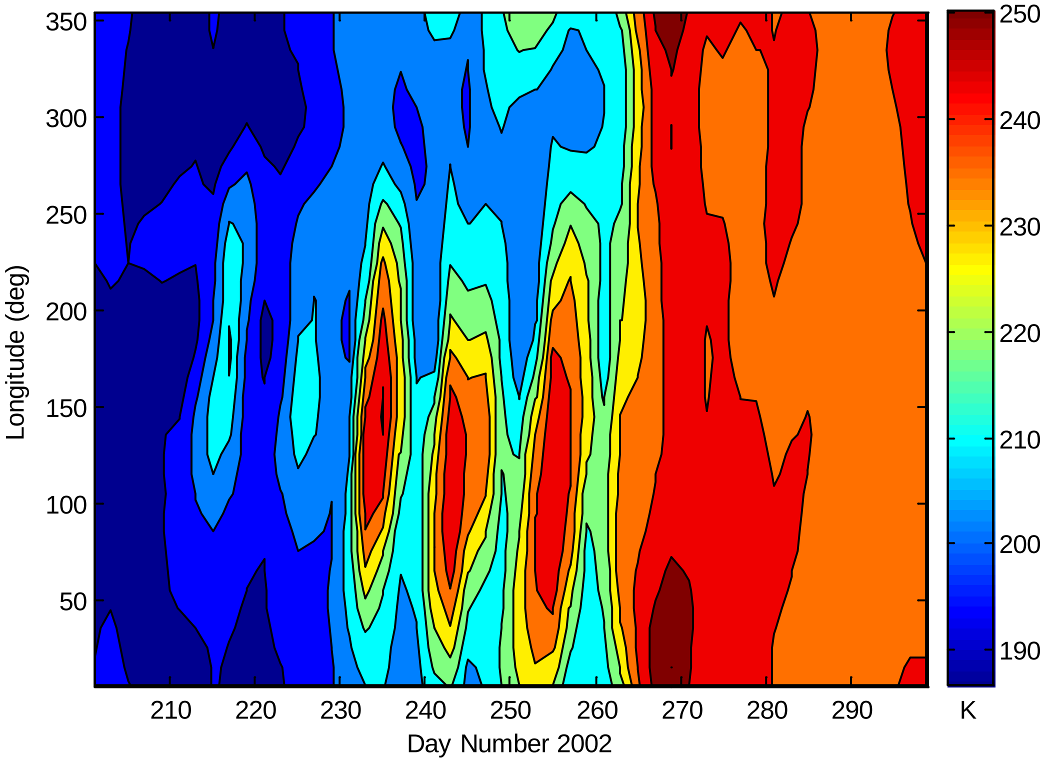


Figure 2. The magnetic latitude (MLAT) location of (a) northern and (b) southern equatorial ionization anomaly (EIA) crest; The TEC of (c) northern and (d) southern EIA crest; the (e) equatorial electrojet (EEJ), (f) polar stratospheric temperature (at 90°S, 10hPa) and (g) zonal wind (at 60°S, 10hPa) from National Centers for Environment Prediction; the (h) Geomagnetic activity index, Kp and (i) solar flux index F10.7 during the period from July 20, 2002 to October 27, 2002.



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330 **Figure 3.** The contour map of polar stratospheric temperature (80°S, 10hPa) obtained from NCEP during

331 the same period as in Figure 2.

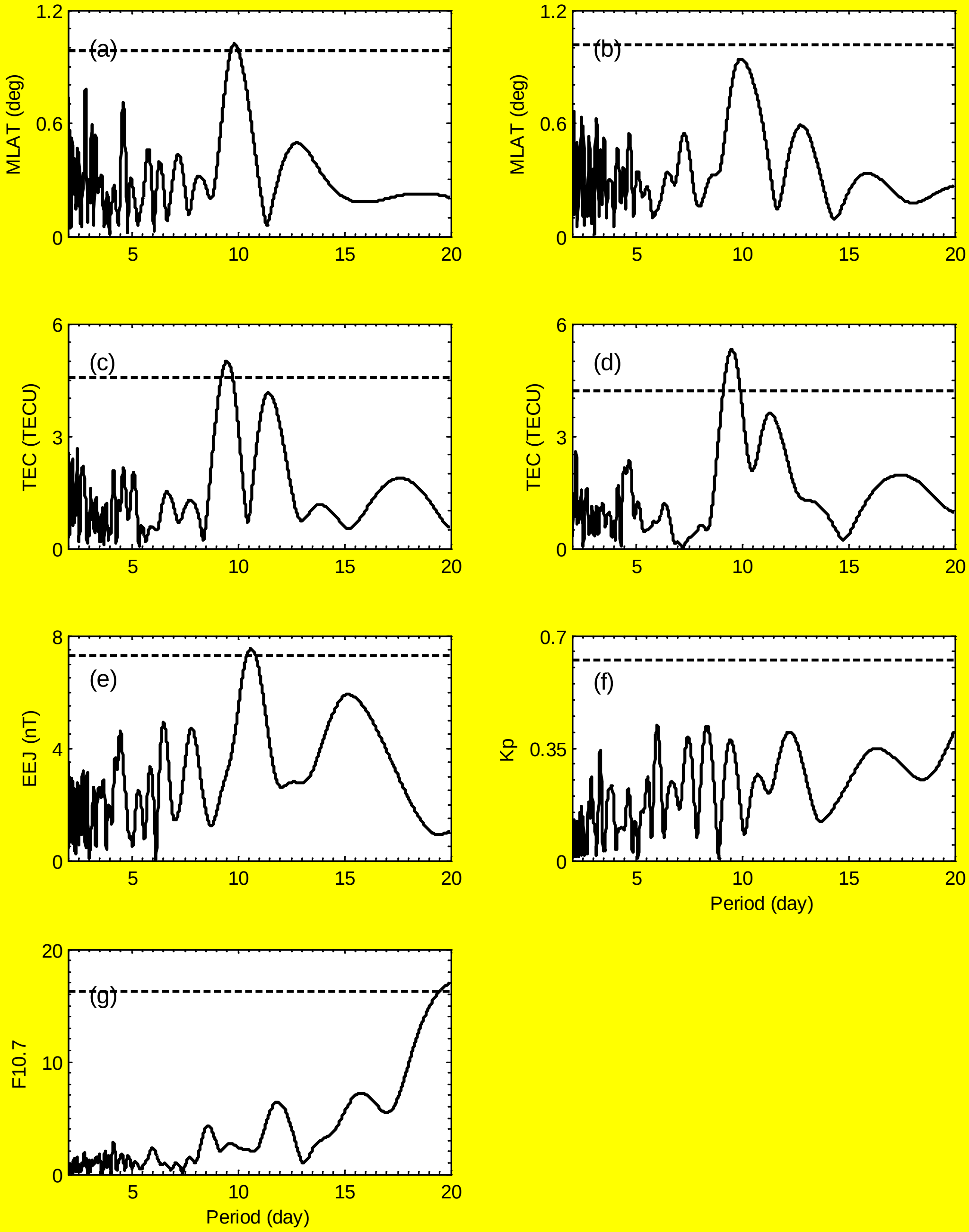


Figure 4. Lomb-Scargle periodgrams of the MLAT location of (a) northern and (b) southern EIA crest, the TEC of (c) northern and (d) southern EIA crest, (e) EEJ, (f) Kp index and (g) F10.7 during the same period as in Figure 2.

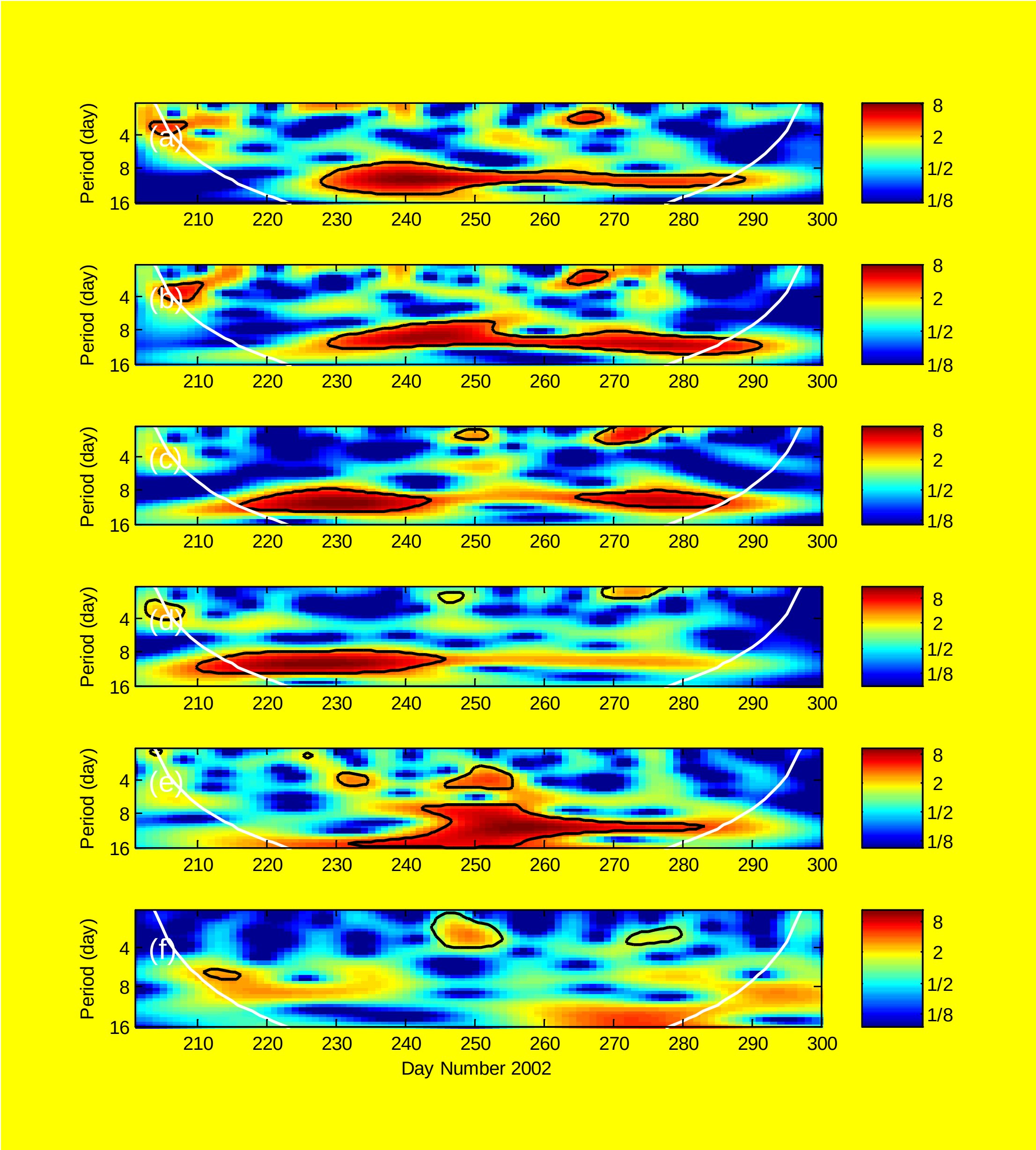


Figure 5. The wavelet power spectra of the MLAT location of (a) northern and (b) southern EIA crest, the TEC of (c) northern and (d) southern EIA crest, (e) EEJ and (f) Kp index during the same period as in Figure 2. The white line in each panel represents the cone of influence of the wavelet analysis.

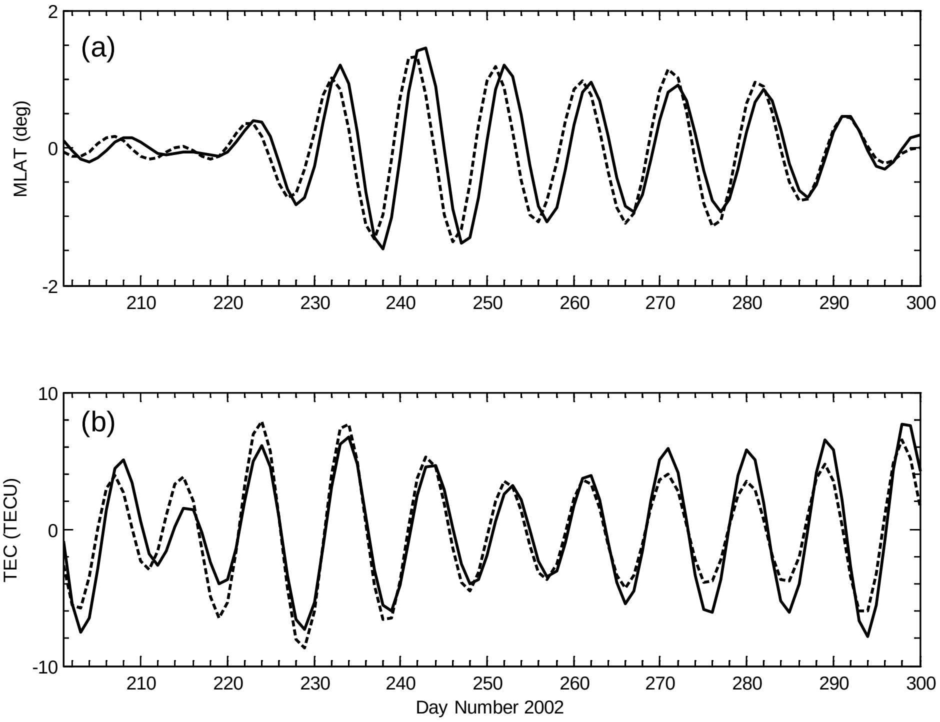
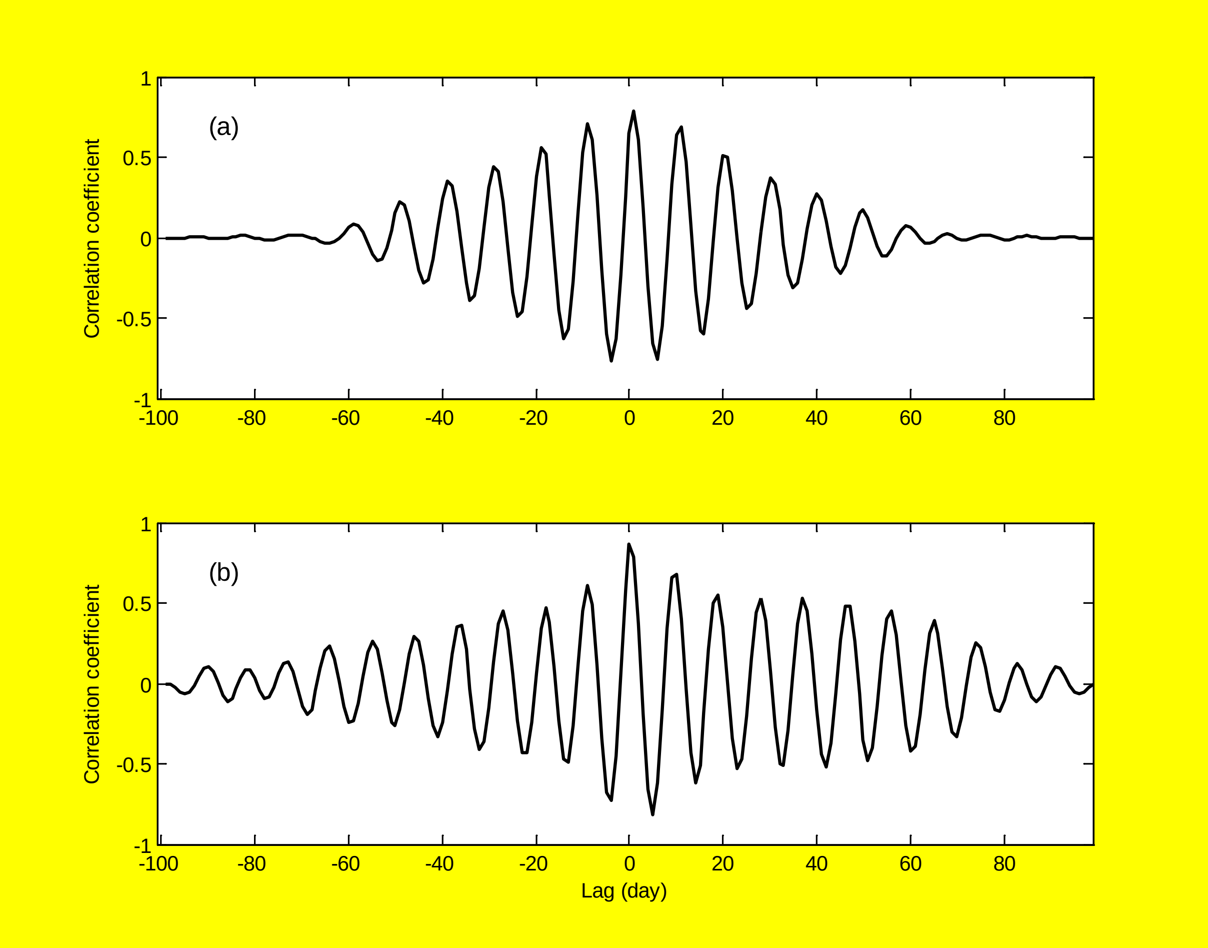


Figure 6. The band-pass filter results of the (a) MLAT location of (solid line) northern and (dash-dotted line) southern EIA crest, the (b) TEC of (solid line) northern and (dash-dotted line) southern EIA crest during the same period as in Figure 2.



344

345 **Figure 7.** The cross-correlation of quasi 10-day waves in MLAT location (a) and TEC (b) between northern

346 and southern EIA crest.