Observational evidence of ionospheric migrating tide modification during the 2009 stratospheric sudden warming


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[1] In this paper, modifications of the ionospheric tidal signatures during the 2009 stratospheric sudden warming (SSW) event are studied by applying atmospheric tidal analysis to ionospheric electron densities observed using radio occultation soundings of FORMOSAT-3/COSMIC. The tidal analysis indicates that the zonal mean and major migrating tidal components (DW1, SW2 and TW3) decrease around the time of the SSW, with 1.5–4 hour time shifts in the daily time of maximum around EIA and middle latitudes. The typical ionospheric SSW signature: a semi-diurnal variation of the ionospheric electron density, featuring an earlier commencement and subsidence of EIA, can be reproduced by differenting the migrating tides before and during the SSW period. Our results also indicate that the migrating tides represent ~80% of the ionospheric tidal components at specific longitudes, suggesting that modifications of the migrating tides may be the major driver for producing ionospheric changes observed during SSW events, accounting for greater variability than the nonmigrating tides that have been the focus of previous studies. Citation: Lin, J. T., C. H. Lin, L. C. Chang, H. H. Huang, J. Y. Liu, A. B. Chen, C. H. Chen, and C. H. Liu (2012), Observational evidence of ionospheric migrating tide modification during the 2009 stratospheric sudden warming, Geophys. Res. Lett., 39, L02101, doi:10.1029/2011GL050248.

1. Introduction

[2] A stratospheric sudden warming (SSW) is a meteorological event where the stratospheric temperature increases rapidly in the winter polar region due to the abrupt slowdown or reversal of the polar westerly vortex by quasi-stationary planetary waves (QSPWs) [Matsumo, 1971]. An SSW can last for several days or weeks as QSPWs with downward or reversal of the polar westerly vortex by quasi-stationary planetary waves [e.g., Liu and Roble, 2002; Chang et al., 2009; Pancheva et al., 2009]. Using NCAR TIME-GCM, Liu et al. [2010] demonstrates that QSPW activity associated with SSWs interacts nonlinearly with pre-existing tides and modulates migrating and nonmigrating tides globally. Fuller-Rowell et al. [2011] simulates the thermosphere and ionosphere electrodynamical response to the 2009 SSW using the Whole Atmosphere Model (WAM). Their simulation shows a substantial increase in the amplitude of the 8-hour terdiurnal tide in the lower thermosphere dynamo region (~120 km altitude), which has a significant impact on the diurnal variation of the electrodynamics at low latitude ionosphere. The model predictions coincide with recent observations of the equatorial upward E × B plasma drift during the SSW, characterized by a morning enhancement and afternoon reversal [e.g., Chau et al., 2009; Anderson and Araujo-Pradere, 2010]. Modification of the equatorial E × B drift leads to the earlier appearance and shorter duration (or earlier subsidence) of the EIA crests, resulting in electron density enhancement in the morning/early afternoon and decrease in the afternoon [e.g., Goncharenko et al., 2010a].

[3] Day-to-day variation of the ionospheric migrating and nonmigrating tidal components have been examined using global ionospheric map TEC (GIM-TEC) and electron density profiles retrieved by FORMOSAT-3/COSMIC (F3/C) satellites. Pedatella and Forbes [2010] extracted tidal components from GIM-TEC, resolving an enhancement of the semi-diurnal westward wave-1 (SW1) nonmigrating tide due to nonlinear interaction between PW1 and the migrating semidiurnal tide (SW2) during the 2009 SSW. Pancheva and Mukhtarov [2011] reported that, using F3/C data at the mid- and low-latitude ionosphere, the zonal and time mean of ionospheric foF2 and the DW1 amplitude of electron density at fixed height show negative responses to the SSW temperature pulses.

[4] Although modification of the migrating and nonmigrating tides during the SSW have been examined individually by previous studies, the relative importance of the migrating and nonmigrating ionospheric tidal responses in generating the observed SSW ionospheric variability have not been studied in detail. In this study, we apply tidal decomposition to global observations of ionospheric peak electron density (NmF2) obtained by F3/C. The modifications of ionospheric migrating and nonmigrating tidal signatures during this time are shown, and their relative

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importance in producing ionospheric variability during the 2009 SSW is examined.

2. FORMOSAT-3/COSMIC Data Analysis

The 2009 SSW presents unique conditions for studying stratosphere-ionosphere coupling due to a particularly strong and long lasting warming effect during deep solar minimum conditions. It is known that SSWs can last for several days or weeks, Goncharenko et al. [2010b] found that perturbations in the EIA were observed for up to 3 weeks after the peak in high-latitude stratospheric temperatures. Similarly, observations from ground-based GPS-TEC and electron densities retrieved from F3/C indicate that the signature of ionospheric response to 2009 SSW event occurred during DOY 022-047 (Lin et al., Observations of

Figure 1. Day-to-day variations of (a) zonal and time mean NmF2 and (b) amplitudes of diurnal westward wavenumber 1 (DW1), (c) semi-diurnal westward wavenumber 2 (SW2), (d) ter-diurnal westward wavenumber 3 (TW3) and (e) semi-diurnal westward wavenumber 1 (SW1) during DOY 001-055 2009. Solid lines overplotted in each frame are averaged stratospheric temperature between 60°-90° latitudes at 10 hPa potential height obtained from radio occultation soundings of F3/C.
global ionospheric responses to the 2009 stratospheric sudden warming event by FORMOSAT-3/COSMIC, manuscript submitted to Journal of Geophysical Research, 2011 hereinafter referred as Lin et al., submitted manuscript, 2011). For the F3/C satellites, one needs to accumulate around 20-day observations to obtain the full global and local time coverage required for unambiguous tidal retrieval. In this paper 20-days of ionospheric peak electron density (NmF2) data (with storm days removed) are binned into a $5^\circ \times 5^\circ$ grid in geographic longitudes and magnetic latitudes between $\pm 40^\circ$ magnetic latitude (MLAT) with the time interval of one hour in local time. The 20-day window is then moved through the time series with steps of one day in order to obtain the daily values.

[6] The NmF2 are further analyzed in terms of their various migrating and nonmigrating tidal components. Similar to analysis of solar atmospheric tides [e.g., Zhang et al., 2006; Pedatella and Forbes, 2010], the NmF2 are fit to the following harmonic functions by using the least-squares method:

$$X(tLT, \lambda) = \bar{X} + \sum_{n=1}^{4} \sum_{\omega = -4}^{4} A_{n,\omega} \cos[n\Omega tLT - (n + s)\lambda + \theta_{n,\omega}]$$

$$+ \sum_{s=1}^{4} A_{0,s} \cos[-(s)\lambda + \theta_{0,s}].$$

[7] Where $X$ denotes the binned observational data, $\bar{X}$ the zonal and time mean, $n$ is subharmonics of a solar day, $\Omega$ is the rotation rate of the Earth (2\pi/day), $t_{LT}$ the local time, $s$ the zonal wavenumber propagating in the eastward (positive values) or westward (negative values) direction, and $\lambda$ the longitude, while $A_{n,\omega}, \theta_{n,\omega}$ and $A_{0,s}, \theta_{0,s}$ are amplitudes and phases of migrating/nonmigrating tides and stationary planetary wave, respectively. The $n = 1, 2, 3$ components are referred to as diurnal, semi-diurnal, and ter-diurnal tides, respectively. The fit is performed for $n = 0, 1, 2, 3$ and $s = -4, -3, \ldots, 3, 4$ and a nearly full spectrum of migrating/sun-synchronized ($n + s = 0$) and nonmigrating ($n + s \neq 0$) tidal components and stationary planet waves for a range of latitudes are obtained.

3. Results and Discussion

[8] Figure 1 shows the day-to-day variations of the retrieved zonal and time mean ($\bar{X}$) and amplitudes of migrating (DW1, SW2 and TW3) and SW1 nonmigrating tide during DOY 001-055 2009. The zonal and time mean shows a clear reduction and hemispheric asymmetry during DOY 020-040 in both northern and southern EIA regions (15°–40° MLAT), before returning to a larger value symmetrically in both hemispheres. Similar reductions during DOY 020-040 are seen in DW1 amplitude at EIA regions and TW3 around the magnetic equator. Reductions in the zonal and time mean and the DW1 are consistent with those reported by Pancheva and Mukhtarov [2011]. It is noted that the decrease of TW3 amplitude occurred only during the SSW period when inspecting the TW3 variations during DOY 305 2008 - DOY 055 2009 (figure not shown). The SW2 shows apparent reductions in the southern EIA region after DOY 020, whereas intensifications of SW2 in the northern EIA region appear after DOY 030. The SW1 nonmigrating tide weakens as early as DOY 015 followed by major intensifications in both hemispheres after DOY 030. The intensifications coincide with amplitude enhancement of SW2. Appearance of SW2 reduction before the peaked stratospheric temperature may be related to the reversal of the zonal mean zonal wind (from eastward to westward). The strong westward wind in the MLT region could decrease the strength of westward propagating tides prior to the SSW [Pedatella and Forbes, 2010].

[9] Electron density observations indicate that the ionospheric SSW effect is characterized by a morning enhancement and afternoon reduction [Goncharenko et al., 2010a]. Lin et al. (submitted manuscript, 2011) show that during the 2009 SSW the global ionosphere reveals a strong electron density reduction for several hours in the afternoon period, while the morning enhancement occurs for a shorter duration. It is also known that the usual EIAs become well
developed and the electron densities therein are stronger during afternoon period than morning. Therefore, the SSW related short-period morning enhancement and prolonged afternoon reduction in the electron densities may be reflected in the decrease of the zonal and time mean. The effect may also decrease the amplitudes of DW1, SW2 and TW3. Unlike the DW1 and TW3, SW2 intensified after DOY 030, after the stratospheric temperature reaches its maximum on DOY 024. Similar results were reported by Pedatella and Forbes [2010], who attributed the SW2 enhancement to enhanced eastward mean winds in the post-SSW period due to forcing by PW1 upon the middle atmosphere mean flow [cf. Liu et al., 2010]. Enhancement of the nonmigrating SW1 may result from nonlinear interaction between PW1 and SW2, which generates SW1 as a byproduct [Chang et al., 2009]. It is noted that while SW1 has comparable amplitudes to TW3, it is only ~10% and ~50% of DW1 and SW2 amplitudes, respectively.

Fuller-Rowell et al. [2011] show that the 2009 SSW related modifications of thermospheric SW2 and TW3 become prominent on DOY 024 in the Whole Atmosphere Model (WAM), while Goncharenko et al. [2010a] show that the low-latitude TECs are modified largely on DOY 027. The reductions of zonal and time mean, migrating and nonmigrating tides shown in Figure 1 coincide with these studies. In Figure 2, we compare the local time variation produced by individual migrating tidal components before (DOY 009) and during (DOY 028) the SSW. Clear amplitude reductions and phase shifts are seen in each of the three migrating tides. DW1 has a daily maximum occurring at 13.5 LT in the northern hemisphere (14.5 LT in the southern hemisphere), approximately 1.5 hours earlier than before the SSW. Similarly, there are 2.5–3.5 and 4 hour time shifts for SW2 and TW3 (around EIA and middle latitudes), respectively. Comparing the superposition of the three migrating tides before and during the SSW, a feature of semi-diurnal variation similar to GPS-TEC variation reported by Goncharenko et al. [2010a, 2010b] is obtained (Figure 2i). This result suggests that modification of ionospheric migrating tides alone can produce the typical ionospheric response to the SSW. Fuller-Rowell et al. [2011] report that the migrating tides in the lower thermosphere dynamo region are substantially modified during the 2009 SSW, where the TW3 showed a substantial increase at the expense of the more typical SW2. It is noted that the ionospheric tidal components may not exactly correspond to the components of thermosphere. The thermospheric SW2 and TW3 perturbations in the E-region could affect the dynamo processes leading to perturbations in diurnal vertical E×B drift and ionospheric electron densities. The thermospheric results reported by Fuller-Rowell et al. [2011] and the ionospheric results obtained from F3/C indicate that variations of the migrating tide during the SSW may be the major driver responsible for the ionospheric electron density variations during this time. The importance of migrating tidal variations responsible for the SSW ionospheric effect is further elucidated in Figure 3, which shows that the superposition of the migrating tides alone represent more than 80% of the ionospheric local time variation resulting from all (both migrating and nonmigrating) tidal components.

The earlier time shifts of the three migrating tidal maxima similar to those shown in Figure 2 can be derived from the initial phases after applying the harmonic fitting.
For migrating tides, each of their cosine function reaches its maximum when

$$t_{LT.MAX} = -\frac{\theta_{LT}}{nQ} = -\frac{\theta_{LT}}{n} \frac{24}{2\pi} \quad (2)$$

From this, the occurrence time of first daily maximum of each migrating tidal component can be obtained. Figure 4 shows the day-to-day variations of occurrence times of maximum amplitudes of DW1, SW2 and TW3 derived from their initial phases using (2). The phase shifts appear around DOY 020-050, and become more prominent around DOY 028-040 at EIA latitudes. The largest time shifts for DW1 and SW2 at EIA latitudes are 1.5 and 4 hours, respectively. The largest time shift for TW3 occurred around EIA and middle latitude is about 4 hours. It is noted that the maximum amplitude of TW3 appear around the magnetic equator, however the time shift is not obvious therein. It is also interesting that the most prominent time shifts of migrating tides are seen around DOY 035 (Figure 4), several days after the stratospheric temperature maximum at DOY 024. The time delay of ionospheric response is consistent with other observation results [e.g., Goncharenko et al., 2010b; Pedatella and Forbes, 2010] as well as theoretical model.

![Figure 4](image-url)
prediction [e.g., Liu et al., 2010], although the mechanism is not clear.

[12] In conclusion, the day-to-day variations of amplitudes and phases of ionospheric tidal components (Figures 1 and 4) can be applied to study the ionospheric electron density modification and time shift of daily maximum related to the 2009 SSW. The ionospheric tidal components extracted from F3/C electron density observations indicate that the variations of migrating tidal components represent the majority (~80%) of the ionospheric SSW effect (Figures 2 and 3), as opposed to the nonmigrating tides, which play a secondary role. In the future, the observational results presented here could compare with tidal signatures of ionospheric electron density output from whole atmosphere models and further correlate with neutral atmospheric tides therein to verify relative importance of SSW related tides.

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