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Ionospheric effects of sudden stratospheric warming during moderate-to-high solar activity: Case study of January 2013

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[1] A major sudden stratospheric warming (SSW) occurred in January 2013 during moderate-to-high solar activity conditions. Observations during the winter of 2012/2013 reveal strong ionospheric disturbances associated with this event. Anomalous variations in vertical ion drift measured at the geomagnetic equator at Jicamarca (12°S, 77°W) are observed for over 40 days. We report strong perturbations in the total electron content (TEC) that maximize in the crests of equatorial ionization anomaly, reach 100% of the background value, exhibit significant longitudinal and hemispheric asymmetry, and last for over 40 days. The magnitude of ionospheric anomalies in both vertical drifts and TEC is comparable to the anomalies observed during the record-strong SSW of January 2009 that coincided with the extreme solar minimum. This observation contrasts with results of numerical simulations that predict weaker ionospheric response to the tidal forcing during high solar activity. **Citation:** Goncharenko, L., J. L. Chau, P. Condor, A. Coster, and L. Benkevitch (2013), Ionospheric effects of sudden stratospheric warming during moderate-to-high solar activity: Case study of January 2013, *Geophys. Res. Lett.*, *40*, 4982–4986, doi:10.1002/grl.50980.

1. Introduction

[2] Numerous observational and modeling studies conducted within the last 3–4 years have demonstrated significant ionospheric variability in association with large-scale meteorological events known as sudden stratospheric warmings (SSWs) [*Chau et al.*, 2012 and references therein]. Such variability is particularly large in the low-latitude ionosphere and includes perturbations in the vertical ion drift [*Chau et al.*, 2009; *Fejer et al.*, 2010, 2011], equatorial electrojet [*Yamazaki et al.*, 2012], and electron density or total electron content (TEC) [*Goncharenko et al.*, 2010a, 2010b; *Liu et al.*, 2011; *Pancheva and Mukhtarov*, 2011; *Lin et al.*, 2012]. Numerical simulations have interpreted such observations in terms of variations in various tidal modes that can get strongly modified during SSW events and then affect the ionosphere via the modified *E* region dynamo [*Fuller-Rowell et al.*, 2010; *Jin et al.*, 2012; *Pedatella and Liu*, 2013].

[3] The majority of earlier studies focused on the analysis of recent SSW events that occurred during the solar minimum. While it became generally accepted that low-latitude ionosphere could get strongly perturbed by tidal variations during solar minimum due to the low background ionospheric electron density, the situation is less clear for high solar activity conditions. *Yamazaki et al.* [2012] used long-term magnetometer data at a single station and concluded that SSW-associated amplifications in lunar tide do not have a clear dependency on solar activity. *Fejer et al.* [2011] have analyzed Jicamarca vertical drift perturbations in lunar tides and concluded that, at high solar flux, the perturbations have smaller amplitudes and larger phase shifts as compared to low solar flux. This contrasts with case studies of January 2003 SSW when large disturbances in vertical drift were reported during high solar activity [*Fejer et al.*, 2010; *Anderson and Araujo-Pradere*, 2010].

[4] Numerical simulations indicate that ionospheric variations in response to the tidal forcing are weakened with the increase in the solar activity due to the higher *F* region Pedersen conductivity [*Liu and Richmond*, 2013], contributions from the *F* region neutral winds [*Maute et al.*, 2012], and in situ generated tides [*Jones et al.*, 2013]. The reduction in vertical drift perturbations with increase in solar activity varies from 30% to almost a factor of 2 depending on the simulation [*Maute et al.*, 2012; *Pedatella et al.*, 2012; *Pedatella and Liu*, 2013].

[5] In this study, we use observations of vertical plasma drift and TEC to examine how the low-latitude ionosphere responds to a major SSW that occurred in January 2013 and coincided with the increase in solar flux up to $F_{10.7}$ = 140–175. The goal of this study is to document the variations in ionospheric parameters associated with the SSW using the wealth of experimental data that was not available during the previous solar maximum (2000–2002). As the current 11 year solar cycle is near its maximum, our results indicate what kind of ionospheric perturbations can be expected from lower atmospheric forcing for solar maximum conditions.

2. Stratospheric Anomalies

[6] Figure 1 gives an overview of anomalies in stratospheric parameters at 10 hPa (~32 km) during the December 2012 to March 2013 period using National Center for Environmental Prediction data. A major sudden stratospheric warming developed in early January 2013, as indicated by a rapid increase in stratospheric temperature (Figure 1a) and a change in the direction of the zonal mean zonal wind (Figure 1b). This SSW event was driven by a strong amplification in planetary wave 1

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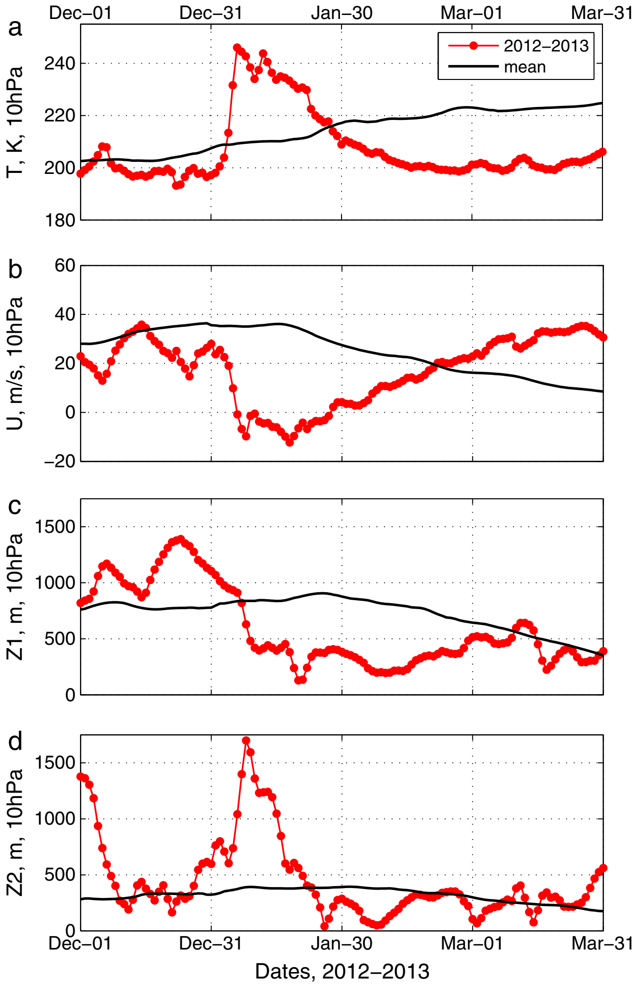

Figure 1. Stratospheric parameters during the winter of 2012/2013. (a) Temperature at 90°N and 10 hPa, (b) zonal mean zonal wind at 60°N and 10 hPa, and (c) wave 1 and (d) wave 2 at 10 hPa, 60°N geopotential height amplitudes. Black lines indicate means from 30 years of data, and red lines indicate the parameters for the winter of 2012/2013.

(Figure 1c) and started as a vortex shift event. During the main phase of SSW, anomalous stratospheric conditions include a strong amplification in planetary wave 2 and a vortex split pattern of polar disturbances (not shown here). This SSW event was one of the strong and prolonged disturbances comparable to those that occurred in January 2006 and January 2009 [*Manney et al.*, 2009].

[7] Although stratospheric disturbances were clearly strong and long lasting, the magnitude of anomalies was weaker than in the record-strong SSW of January 2009 [compare with Figure 1, *Goncharenko et al.*, 2010b]. Peak stratospheric temperature reached 244 K (in comparison with 265 K in SSW 2009) while the zonal wind reached −12 m/s (in comparison with −29 m/s in SSW 2009). The amplitude of planetary waves was approximately comparable for the two SSW events.

3. Ionospheric Anomalies

[8] Figure 2 displays the variation in the total electron content (TEC) measured along geographic longitude 75°W at local noon (12 LT, 17 UT) from 1 December 2012 to 28 February 2013 (TEC units: 10^{16} el/m^2). The TEC reaches its maximum values in two latitudinal bands located at ~10–15° to the north and south of the geomagnetic equator (12°S for 75°W longitude), a phenomena well known as equatorial ionization anomaly (EIA). Electron density in the low-latitude ionosphere has a positive correlation with solar radio flux and is known to depend on geomagnetic activity [*Rishbeth*, 2000, and references therein]. In the case of winter 2012-2013, the solar flux index reached the level of $F_{10.7} = 174$, one of the highest levels for the current 11 year cycle of solar activity. The geomagnetic activity varied from predominantly quiet to minor storm conditions. The most distinct variation in TEC during this time period is a multiday increase in both northern and southern peaks of the EIA magnitude observed in mid-January (Figure 2). A similar but weaker increase is also observed from late December to early January. The mid-January increase cannot be driven by variation in the solar flux that peaked 7 days earlier, on 10 January. Brief moderate geomagnetic activity (up to $Ap3 = 22$–27, $Kp = 4$- to 4) is also not expected to drive such TEC variations. Similarly, a weaker TEC increase observed in late December to early January is not related to either solar or geomagnetic activity. These TEC increases are consistent with variations that can be produced by enhanced daytime electric field, as both the northern and southern crests of EIA are affected, and location of EIA crests moves to higher latitudes [*Kelley*, 2009].

[9] Strong variations in the daytime vertical ion drift have been previously associated with sudden stratospheric warmings and solar minimum conditions [*Chau et al.*, 2009; *Goncharenko et al.*, 2010a]. In this study, we use a combination of vertical drift data from Jicamarca (77°W, 12°S) Unattended Long-term Investigations of the Ionosphere and Atmosphere radar and magnetometer to extend the temporal coverage (see *Chau et al.*, 2012, for discussion of experimental techniques). Observations demonstrate that the vertical ion drift was

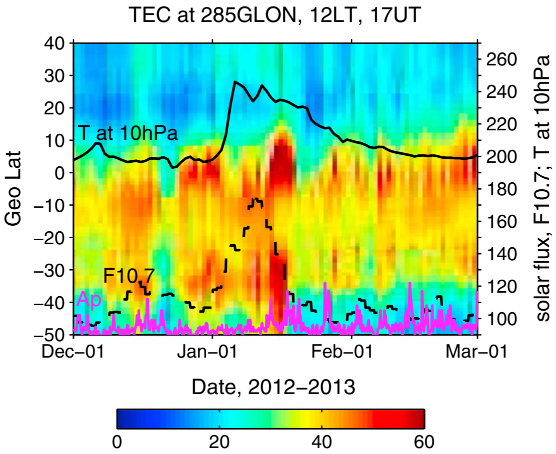

Figure 2. Observations of TEC at 75°W and 12 LT as a function of day and latitude. Dashed black line shows $F_{10.7}$ index, magenta line shows $Ap3$ index, and solid black line shows stratospheric temperature at 90°N and 10 hPa. $Ap3$ index is shifted by 90 units to use the same scale as $F_{10.7}$ index. Stratospheric warming coincides with the increase in $F_{10.7}$. The largest ionospheric disturbances during the winter of 2012/2013 are observed in mid-January and are associated with an SSW event.

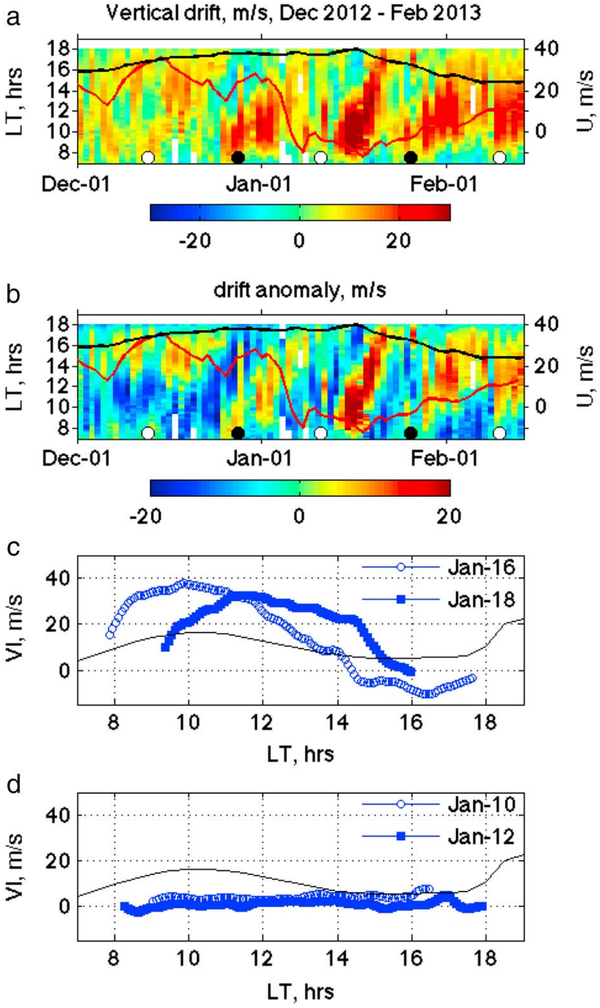

Figure 3. Observations of vertical drift at Jicamarca location (12°S, 77°W). (a) Drift data as a function of day and local time. Black line indicates the 30 year mean zonal mean wind in the stratosphere, 10 hPa, and 60°N. Red line shows stratospheric zonal mean wind in 2012/2013. The circles indicate dates of full moon (full circles) and new moon (open circles). (b) Drift anomaly (drift observations minus climatological average). (c) Observations on 16 January and 18 January demonstrate strongly upward drift in the morning sector and progressive shift to later local times. Black line shows the Scherliess-Fejer model result. (d) Observations on 10 January and 12 January demonstrate suppression of expected drift behavior for the entire day.

indeed strongly anomalous in December 2012 to January 2013. Figure 3a presents the daytime vertical drift while Figure 3b presents the drift anomaly (drift observations minus Scherliess-Fejer climatological model [*Scherliess and Fejer*, 1999]). The typical SSW feature appears in the vertical drift data as morning enhancement and afternoon decrease, in a quasi semidiurnal pattern that progresses to later local times within several days. Maximum positive drift anomaly is observed on 15–19 January, with upward vertical drifts reaching 30–43 m/s. This is comparable to the vertical drifts (~30–52 m/s) observed during several most disturbed days of the record-strong SSW of January 2009 [*Chau et al.*, 2010], although the SSW 2013 is a weaker event. The vertical drift enhancements are preceded and followed by multiday mostly negative drift anomalies (23–27 December, 4–12 January, and 21–26 January), forming three cycles as seen in Figure 3b. Peak anomaly drifts do not coincide with the dates of full moon (dark circles) or new moon (light circles) but are observed 4–6 days later, as noted by *Fejer et al.* [2010, 2011] for other SSW events.

[10] Recent numerical simulations [*Jin et al.*, 2012; *Pedatella and Liu*, 2013] suggest that the anomaly in the stratospheric zonal mean wind is the primary cause of modifications in semidiurnal solar and lunar tides that leads to perturbations in the low-latitude ionosphere. In addition, *Pedatella and Liu* [2013] demonstrate that the phase of the semidiurnal solar tide changes in a manner that makes it similar to the phase of the lunar semidiurnal tide. Our results are consistent with these simulations. As shown in Figures 1b and 3a, stratospheric zonal mean zonal wind was significantly weaker than average since mid-December 2012 and remained strongly anomalous until mid-February. The temporal extent of the stratospheric wind anomaly coincides with the temporal extent of the ionospheric vertical drift anomaly (Figures 3a and 3b), supporting suggestions that variations in the middle atmospheric zonal wind alter the vertical propagation of both solar and lunar tides.

[11] While most days exhibit drift variations consistent with the amplification of 12 h tidal mode and negative drift anomaly within 4–8 h after the positive drift anomaly (Figure 3c), there are multiple cases of vertical drift observations close to 0 m/s for the entire day, as illustrated in Figure 3d. Model simulations [*Pedatella and Liu*, 2013] indicate that both solar and lunar migrating semidiurnal tides can be amplified during SSW and have a progressive phase change over several days. Other tides, including nonmigrating semidiurnal and diurnal tides, migrating diurnal tide, and terdiurnal tide can also be amplified [*Fuller-Rowell et al.*, 2010; *Jin et al.*, 2012; *Lin et al.*, 2012]. Constructive superposition of the solar migrating 12 h tide, lunar 12 h tide, and other tidal modes can lead to the enhancement of low-latitude vertical drift as demonstrated in Figure 3c while destructive superposition can cause abnormally low vertical drift as shown in Figure 3d.

[12] Figure 4 examines the longitudinal difference in TEC behavior during winter 2012/2013 and demonstrates variations in TEC as a function of date and local time in the American longitudinal sector (75°W, top row), East African sector (40°E, middle row), and Asian sector (150°E, bottom row). We subtracted the seasonal TEC behavior (obtained for every longitude, latitude, and local time bin as polynomial fit to 3 months of data) from the observed TEC values and express the obtained TEC variations as a percentage of the background expected seasonal value.

[13] Significant variations in the radio solar flux drive only a small portion of the observed variations in TEC, in particular, an ~10%–15% increase in TEC in all daytime hours at the magnetic equator (middle panels). The variability with a 2–3 day period is also observed at all three longitudes but will not be addressed in this study. The majority of the observed TEC variation in both the northern and southern EIA crests exhibit behavior consistent with lunar tide phase change [*Fejer et al.*, 2011] and consistent with the vertical drift observations shown in Figure 3, confirming expectations that they are driven by plasma transport strongly affected by solar and lunar tides modified by an SSW event. Such variations

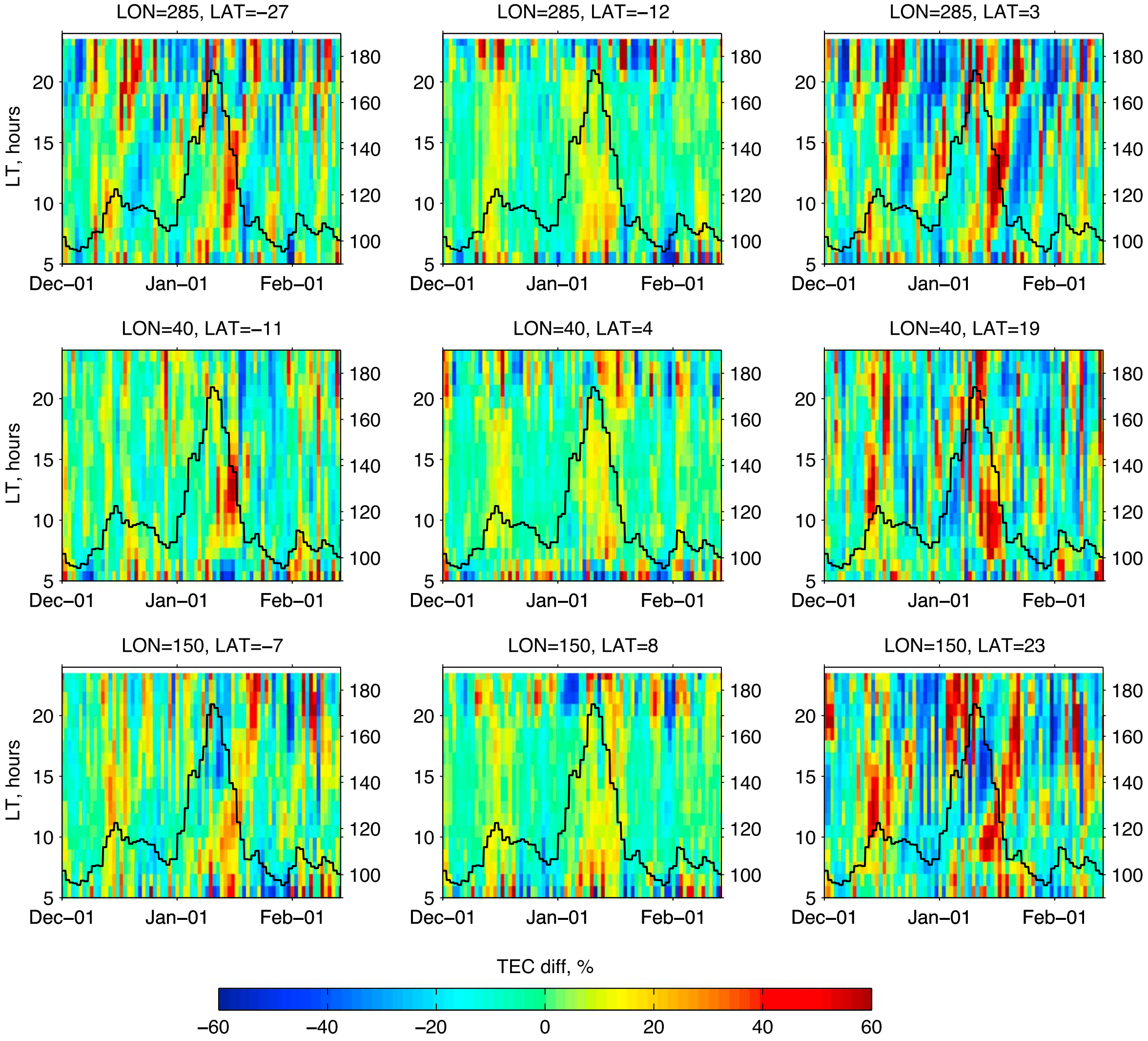

Figure 4. Relative variations in GPS TEC data (expressed as a percentage of background value) at longitudes 75°W (top row), 40°E (middle row), and 150°E (bottom row). Variations are shown for the southern crest of EIA, 15°S geomagnetic latitude (left columns), magnetic equator (middle columns), and northern crest of EIA, 15°N geomagnetic latitude (right columns). Titles indicate geographic coordinates. Black line shows the $F_{10.7}$ index.

start in mid-December as TEC enhancements that are particularly strong at 75°W and experience three cycles, with peaks around mid-December, early January, and mid-January. The northern crests of EIA experience deeper TEC variations than the southern crests at all three longitudes, in consistency with experimental results [*Pedatella and Forbes*, 2010] and Whole Atmosphere Community Climate Model simulations [*Pedatella and Liu*, 2013]. Such variations reach 100%, 60%–70%, and 90%–100% of the background value during daytime hours ($5 < \mathrm{LT} < 19$) in the northern crest of EIA at 75°W, 40°E, and 150°E, respectively, and can exceed 100% after 19 LT. In the southern crests of EIA, TEC variations reach 40%–45% at 75°W, 60%–70% at 40°E, and up to 30%–40% at 150°E.

4. Summary

[14] We present the analysis of ionospheric anomalies in vertical drift and total electron content observed at low latitudes during the winter of 2012/2013 in conjunction with a major sudden stratospheric warming. The warming was one of the strongest and prolonged events, though still weaker than a record-strong SSW of January 2009. In addition, the SSW event coincided with the increase in the solar activity to the highest levels observed during the current maximum in 11 year solar cycle (up to $F_{10.7} = 140–175$). The primary results are as follows:

[15] 1. Ionospheric anomalies associated with an SSW event are observed for over 40 days, from mid-December 2012 to the end of January 2013. Perturbations from expected background values in both vertical drift and TEC vary as a function of day and local time in consistency with the phase of semidiurnal lunar tide.

[16] 2. Our results are consistent with simulations by *Jin et al.* [2012] and *Pedatella and Liu* [2013] that indicate that anomalies in the stratospheric zonal wind are the main drivers of tidal modifications during SSW. Using two types of independent ionospheric measurements, e.g., vertical drifts and TEC, we provide experimental support for this hypothesis.

[17] 3. Perturbations in TEC reach maximum values of 80%–100% near the crests of equatorial ionization anomaly.

These perturbations are comparable to ionospheric disturbances reported earlier for the record-strong SSW of January 2009 that coincided with a deep minimum in solar activity ($F_{10.7} = 70$) (see supporting information). The TEC perturbations exhibit significant longitudinal and hemispheric asymmetry, with stronger disturbances in the Northern Hemisphere and in the American longitudinal sector (75°W).

[18] 4. These observations contrast available numerical simulations that examine the role of solar activity on ionospheric perturbations due to the tidal forcing and predict weaker ionospheric disturbances for high solar flux conditions. The models predict that the roles of the *F* region Pedersen conductivity, *F* region neutral winds, and in situ generated tides increase for high solar flux conditions to suppress ionospheric perturbations of lower atmospheric origin. Our results indicate that this suppression does not play the dominant role and suggest that the resulting ionospheric impact strongly depends on the details of the perturbed wave dynamics in the middle atmosphere and varies on a case-by-case basis for different SSW events.

[19] 5. Our data indicate that lower atmospheric forcing may play a significant role in ionospheric variability not only during the periods of low solar activity but also during the periods of moderate-to-high solar activity.

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