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Unexpected connections between the stratosphere and ionosphere

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[1] The coupling of the ionosphere to processes from below remains an elusive and difficult problem, as rapidly changing external drivers from above mask variations related to lower atmospheric sources. Here we use superposition of unique circumstances, current deep solar minimum and a record-breaking stratospheric warming event, to gain new insights into causes of ionospheric perturbations. We show large (50–150%) persistent variations in the low-latitude ionosphere (200–1000 km) that occur several days after a sudden warming event in the high-latitude winter stratosphere (~30 km). We rule out solar irradiance and geomagnetic activity as explanations of the observed variation. Using a general circulation model, we interpret these observations in terms of large changes in atmospheric tides from their nonlinear interaction with planetary waves that are strengthened during sudden warmings. We anticipate that further understanding of the coupling processes with planetary waves, accentuated during the stratospheric sudden warming events, has the potential of enabling the forecast of low-latitude ionospheric weather up to several days in advance. **Citation:** Goncharenko, L. P., J. L. Chau, H.-L. Liu, and A. J. Coster (2010), Unexpected connections between the stratosphere and ionosphere, *Geophys. Res. Lett.*, *37*, L10101, doi:10.1029/2010GL043125.

1. Introduction

[2] The Earth's ionosphere, the charged portion of the upper atmosphere with maximum ionization around ~300 km altitude above the ground, is highly variable. Although the primary drivers of this variability are related to solar and geomagnetic activity, on average ~20% of daytime ionospheric variations are linked to processes in the lower atmosphere [e.g., *Forbes et al.*, 2000]. Transfer of energy and momentum from the lower atmosphere to the ionosphere is thought to happen through the upward propagation of atmospheric waves (planetary waves, tides, gravity waves). Though the links between lower atmospheric processes and ionosphere have been demonstrated [e.g., *Rishbeth*, 2006], systematic studies of these links remain a challenging task due to the rapid response of the ionosphere to solar and magnetospheric drivers.

[3] Here we present observations of the ionospheric response to a major meteorological event called a stratospheric sudden warming [*Matsuno*, 1971]. Using the Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model (TIME-GCM), we examine if the observed coupling between the stratosphere and ionosphere can be related to the growth of quasi-stationary planetary waves which become strong during stratospheric warming events.

2. Data and Methods

2.1. GPS TEC Data

[4] For this study, maps of global total electron content (TEC) were obtained from the network of worldwide GPS receivers and calculated using the MIT Automated Processing of GPS (MAPGPS) software suite [*Rideout and Coster*, 2006]. MAPGPS outputs TEC estimates in 1° × 1° bins of latitude/longitude with 5 minutes temporal resolution and distributed over those locations where data is available. The errors in the code are tracked throughout the processing, and error values are calculated independently for each binned measurement. Mean TEC values in Figures 1a and 1b were calculated by averaging the 1° × 1° TEC bins for January 3–12, 2009, and within +/−30 minutes of 15 UT and 21 UT, respectively. The units of GPS TEC data are TECU, where 1 TECU = 10^{16} electrons/m^2. More details on GPS TEC analysis are given by L. P. Goncharenko et al. (Impact of sudden stratospheric warmings on equatorial ionization anomaly, submitted to *Journal of Geophysical Research*, 2010).

2.2. TIME-GCM Model

[5] For the purposes of the study, we use the TIME-GCM model developed at the National Center for Atmospheric Research [*Richmond et al.*, 1992; *Roble and Ridley*, 1994]. The TIME-GCM is a three-dimensional time-dependent model that solves the atmosphere primitive equations and incorporates the known aeronomical and photochemical processes for the middle and upper atmosphere. The model resolution is 5° × 5° in longitude and latitude. We use 49 vertical pressure levels with lower boundary at ~30km and upper boundary at ~480km. As we aim to isolate the impact of an idealized stationary planetary wave 1, two nearly identical numerical simulations are performed, with the stationary planetary wave absent in the base case, and specified in the control case. The stationary planetary wave in the control case is specified at the lower boundary and has a maximum geopotential height perturbation of 2500 m, located at 60°N. The simulations are for January–March period, when the northern hemisphere SSW most often occurs. The solar irradiance spectrum was computed for a 10.7 cm solar radio flux (F10.7) and was held constant throughout the simulation period at the level of 70 solar flux units to reflect solar minimum conditions. The geomagnetic activity was held constant at a very quiet level. Appropriately

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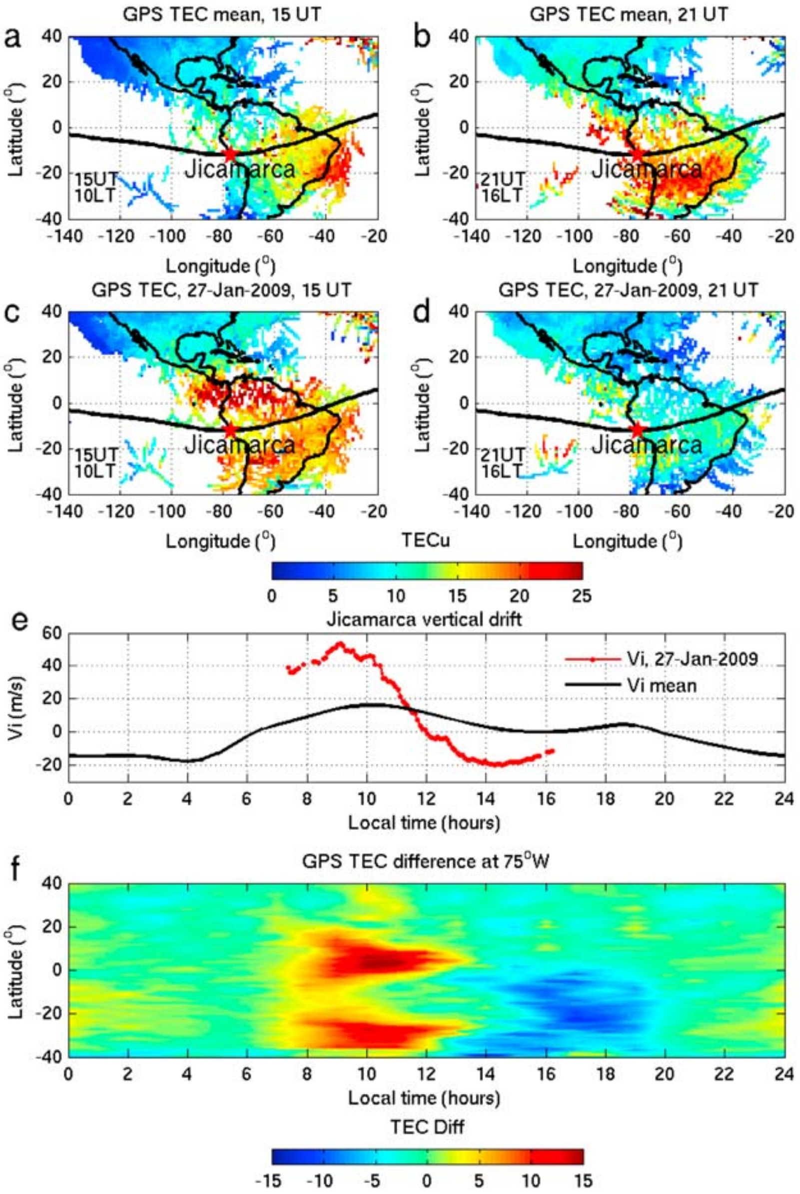

Figure 1. Observations of ionospheric behavior during stratospheric warming. (a) Typical distribution of total electron content (TEC) in the western hemisphere at 15 UT (morning sector, 10 LT at 75°W). Black line shows magnetic equator. Star shows location of Jicamarca radar. (b) Same as Figure 1a, but for 21 UT (afternoon sector, 16 LT at 75°W). (c) TEC in the morning sector (15 UT) on Jan 27, 2009, during SSW. Increase in TEC is observed in the extended range of longitudes and latitudes. (d) TEC in the afternoon sector (21 UT) on Jan 27, 2009. In contrast to observations during morning hours, in the afternoon TEC is decreased. (e) Vertical drift observations by Jicamarca radar (12°S, 75°W) at 200–500 km above ground. Red line presents observations on Jan 27, 2009, during SSW. Black line presents average behavior for winter season and low solar activity. Strong semidiurnal variation is observed during SSW. (f) Change in TEC at 75°W during SSW as function of local time and latitude. Ionospheric variations during SSW are observed during daytime hours.

low and constant levels of auroral precipitation, cross-cap potential fields, and hemispheric power were used. Details of the numerical experiments are given by *Liu et al.* [2010].

3. Results and Discussion

[6] At the end of January 2009, the strongest and most prolonged major Stratospheric Sudden Warming (SSW) on record developed in the stratosphere-mesosphere system [*Manney et al.*, 2009]. This event resulted in dramatic changes in stratospheric temperature and dynamics. We report here that several days after the peak in high-latitude stratospheric temperature, large anomalous variations were observed in the low-latitude ionosphere, as illustrated in Figure 1. The mean TEC between 3 and 12 January 2009 is shown in Figure 1a for 15UT and Figure 1b for 21UT. It is characterized by low TEC in the morning sector (Figure 1a) and higher TEC in the afternoon sector (Figure 1b), with well developed peaks in the Appleton anomaly [*Anderson*, 1981] within ~15° from the magnetic equator. This behavior

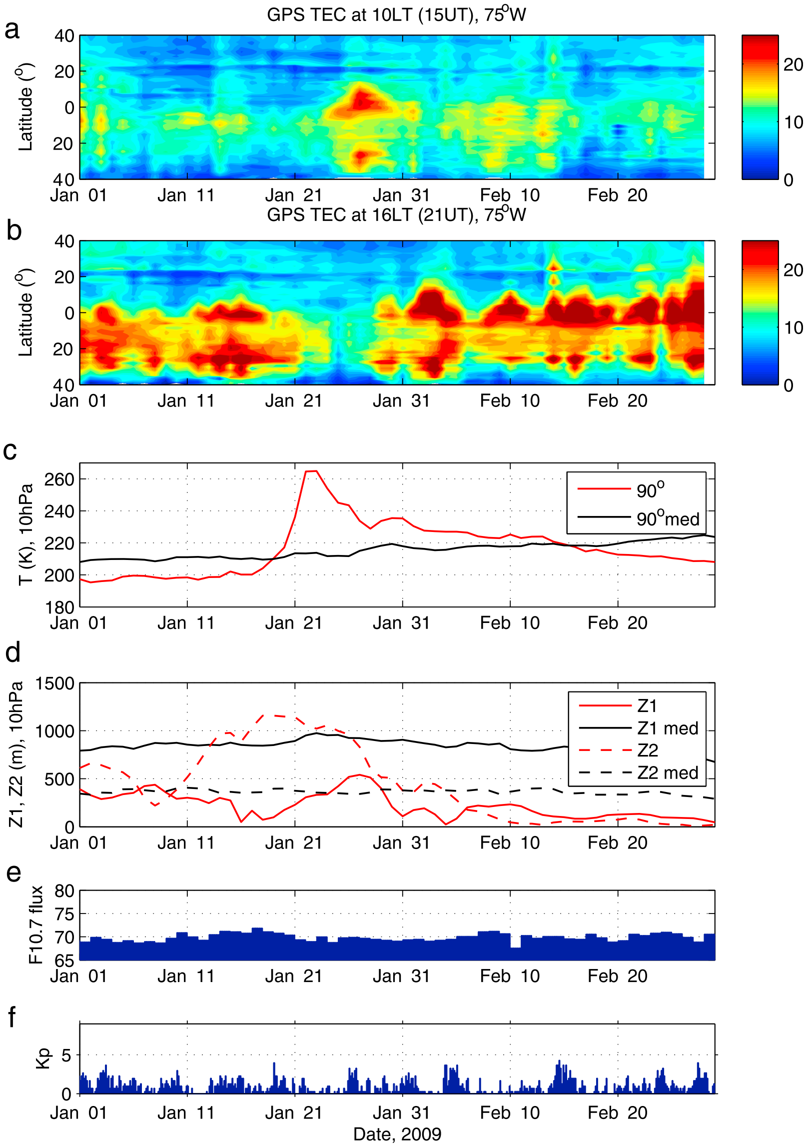

Figure 2. Temporal variation in reported characteristics in January–February, 2009. (a) GPS TEC at 75°W in the morning sector (15 UT) shows increase in TEC after the peak in high-latitude stratospheric temperature, but not at any other time. (b) Same as Figure 2a, but in the afternoon sector (21 UT). Decrease in TEC is observed following the peak in SSW, but not at any other time. (c) Stratospheric temperature at 90°N and 10hPa (~30 km). Red line – data during 2009, black line – 30-year mean. Peak in stratospheric temperature is reached on Jan 23, 2009. (d) Activity of planetary waves 1 (Z1) and 2 (Z2) at 60° N and 10 hPa. Planetary wave 2 activity increased by a factor of ~3 prior to the SSW (e) F10.7 index indicates very low and stable solar activity level. (f) Kp index demonstrates quiet geomagnetic conditions.

drastically changed several days after the peak in SSW. On January 27, 2009, low-latitude TEC is enhanced in the morning hours by 50–150% (Figure 1c), with strong Appleton anomaly and gradients in TEC reaching 2–3 TECU per degree of latitude. In contrast, the TEC is suppressed in the afternoon hours by ~50% (Figure 1d). The magnitude of the variation in low-latitude TEC is comparable to TEC variations observed during major geomagnetic storms [*Mannucci et al.*, 2005].

[7] Simultaneous observations at the magnetic equator by the Jicamarca incoherent scatter radar (12°S, 75°W) indicated anomalous variations in the vertical ion drift (Figure 1e) at altitudes 200–500 km above the ground. A distinctive feature of this variation was a clear semidiurnal signature in the drift, with the same phase as average observations from over 35 years of data, but with much larger amplitude. The difference in the drift exceeded 3 standard deviations. Large positive (upward) drifts were observed in the morning, followed by negative (downward) drifts in the afternoon. The equatorial vertical drift has a direct effect on the low-latitude ionospheric electron density by moving electrons to altitudes and latitudes (via magnetic field lines) where loss rates are different, with slower loss rates at higher altitudes. Analysis of GPS TEC data showed that the anomalous ion drifts indeed changed the structure of the entire daytime ionosphere (Figure 1f). The large upward ion drift in the morning enhanced the Appleton anomaly, so that the TEC increased by up to 20TECu, and downward plasma drift in the after-

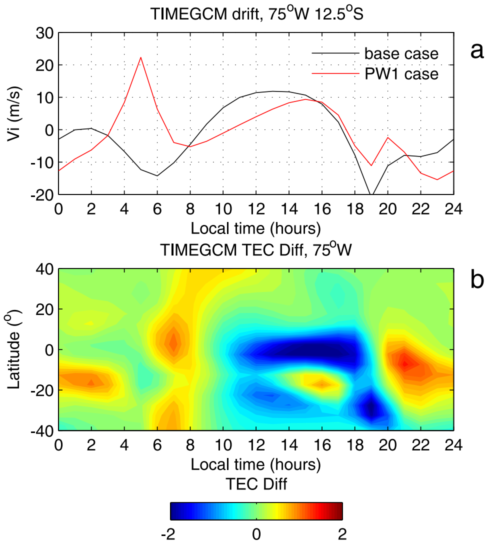

Figure 3. Ionospheric variations predicted by the model. (a) Vertical ion drift for a base case (black line) and planetary wave case (red line) for Jicamarca location (12°S, 75°W). (b) Change in TEC at 75°W due to planetary wave. Compare to Figures 1e and 1f.

noon suppressed the equatorial anomaly, reducing TEC by 10–15TECu. The GPS TEC perturbations are consistent with Jicamarca ISR ion drift observations and are observed over a large range of longitudes and latitudes. The semidiurnal nature of this phenomenon, with maximum at ~10–12 LT (local time) and minimum at 16–18 LT, is also evident in the evening hours, with a secondary weaker increase in TEC at ~24LT.

[8] Figure 2 shows the latitude-time evolution of TEC and time series of stratospheric polar temperature, planetary wave activity, and solar and geomagnetic indices during January and February 2009 The anomalies in the low-latitude ionosphere persisted for several days after the peak in SSW, while the ionosphere remained less variable during other days in January and February 2009 (Figure 2a for 10LT and Figure 2b for 16LT). It is well known that the Earth's ionosphere is a highly variable part of the atmosphere. Rapid response to changes in external forcing (solar irradiance, geomagnetic activity) has long been assumed to be the primary reason for ionospheric variability. However, both solar ionizing flux, as indicated by the F10.7 index (Figure 2e), and geomagnetic activity, as indicated by the Kp index (Figure 2f), were at extremely low and stable levels throughout the winter of 2009, as a consequence of the current deep solar minimum. This allows us to rule out solar and geomagnetic activity as reasons for the observed ionospheric changes. In particular, they cannot explain the semidiurnal nature of the variations and persistence over several days. Lower atmospheric forcing during SSW is then the only conceivable reason for the observed ionospheric variations.

[9] The main features of the ionospheric perturbations observed during the January 2009 SSW appear to be repeatable. Similar perturbations have been observed during other stratospheric warming events with multiple instruments [*Goncharenko and Zhang*, 2008; *Chau et al.*, 2009; Goncharenko et al., submitted manuscript, 2010]. Additional analysis of other events will be presented elsewhere.

[10] Available experimental data demonstrate a link between changes in the high-latitude stratosphere and the equatorial ionosphere. The key problem is to explain how such geographically separated regions are connected with each other in altitude and latitude. The fact that the observed ionospheric variation has a clear semidiurnal pattern, with a maximum at 15UT and a minimum 6 hours later, implies the existence of a strong semidiurnal tide in the low-latitude ionosphere. Since the occurrence of SSWs is related to the growth of quasi-stationary planetary waves [*Matsuno*, 1971], such a strong semidiurnal tide could result from nonlinear interaction between tides and a quasi-stationary planetary wave [*Hagan and Roble*, 2001; *Liu and Roble*, 2002]. The planetary wave 2 activity prior and during the SSW of 2009 was strongly enhanced as compared to the 30-year median activity, as demonstrated in Figure 2d. However, strengthened planetary waves by themselves cannot explain our observations, as they do not propagate to the low latitude ionosphere.

[11] Quasi-stationary planetary waves originate from high latitudes of the winter hemisphere, and are mostly limited to high and middle latitudes [*Pogoreltsev et al.*, 2007; *Pancheva et al.*, 2009]. The vertical propagation of the quasi-stationary planetary waves is confined below the critical layer near mesopause where the zonal wind reverses [*Sassi et al.*, 2002]. A number of mechanisms have been proposed to explain how planetary waves originating in the lower atmosphere could impact the ionosphere [*Forbes*, 1996; *Liu et al.*, 2010]. Quasi-stationary planetary waves, though generally trapped below the mesopause, interact nonlinearly with the tides at lower altitudes causing large changes in both migrating and non-migrating tides. These tides usually have an amplitude maximum at low latitudes and can propagate into the thermosphere. The tidal winds can modulate electric fields through the ionospheric wind dynamo (at ~115 km). At low latitudes, these modulated electric fields map along magnetic field lines to higher altitudes (~250–400 km) and produce tidal variations in vertical ion drifts. There has been growing observational and modeling evidence to support a mechanism which involves non-linear interactions of planetary waves with tidal modes, producing amplification in the amplitude of tidal modes in the mesosphere-lower thermosphere region [*Lieberman et al.*, 2004; *Liu et al.*, 2007]. Our observations of an increased semidiurnal signature in both vertical ion drift at 200–500 km above the ground and in TEC can thus be interpreted as direct evidence of the modulation of the ionospheric E-region dynamo by an enhanced semidiurnal tide [*Liu et al.*, 2010].

[12] To test whether planetary waves can produce a difference in the vertical ion motion in the low-latitude ionosphere and subsequent redistribution of electron density, we examine the ionospheric response to a stationary planetary wave 1 in the TIME-GCM, and compare it to ionospheric simulations without the planetary wave. The simulations show that the E-region dynamo is strongly affected by the tidal wind perturbations, and there are significant changes in the vertical ion drift at the Jicamarca location, with a strong upward change during the early morning hours and downward change around noon (Figure 3a). In agreement with

our observations, the modeled TEC displays a large increase in the morning, probably because the strong upward drift enhances the Appleton anomaly, and a decrease in the afternoon (Figure 3b). The modeled TEC response is 1–2 hours delayed relative to the response in vertical drift, again in excellent agreement with observations. While the simulated ionospheric response is smaller than in the observational data, the model captures the essential characteristics of the observed ionospheric change and demonstrates that introduction of a quasi-stationary planetary wave at high winter latitudes and at the lower boundary (~30 km) leads to perturbations in the ionosphere at low latitudes and at the altitudes of several hundred kilometers.

[13] Based on our observations and modeling results, we conclude that there is a strong link between the perturbations in the high-latitude stratosphere and those in the low-latitude ionosphere. Previous case studies have demonstrated ionospheric variations with planetary wave periods. Some of them were attributed to periodic variations in geomagnetic activity [*Lei et al.*, 2008] or solar ionizing flux [*Pancheva et al.*, 2002], and some were attributed to planetary wave activity [*Forbes and Leveroni*, 1992]. Processes originating at lower altitudes were thought to be responsible for about 20% of daytime ionospheric variations. Our study shows a new type of response not identified before, a semidiurnal wave producing major ionospheric variations. These results are part of an emerging consensus of strong links between the lower and upper atmosphere. Recent studies explored such connections through tidal modes originating from tropospheric heating processes [*Hagan et al.*, 2009] or gravity waves excited by topography, convection or wind shear near Earth's surface [*Vadas*, 2007]. Our study demonstrates that planetary waves, a type of wave generated by the interaction of wind and orography, can have a profound effect on the state of ionosphere.

[14] This observation is particularly important for the low-latitude ionosphere, where large variations in vertical drifts (and therefore electron densities) have been an unresolved problem for decades [*Fejer and Scherliess*, 2001] and where ionospheric irregularities can impact a variety of communication and navigation systems. The observational fact that ionospheric changes we report occur several days after the peak in planetary wave activity in the stratosphere makes it particularly appealing for ionospheric forecasting. Current models operate in a now-casting approach, while ionospheric predictions at least few hours in advance remain a matter of future development. Understanding the physical mechanisms connecting the lower and upper atmosphere will be an essential part of future models aiming for multi-day forecasts and enabling mitigation of ionospheric effects on performance of various radio frequency systems. Considering the upper atmosphere as a part of a complex and evolving Earth system is a necessary step for further advances in understanding and forecasting the geospace environment.

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