AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE

10.1002/2014JA020649

Key Points:

- Using 17 GPS, it is observed that the ionosphere was disturbed by the SSW from equator to midlatitudes
- The EIA was suppressed during the SSW 2009 event
- The SSW event in one hemisphere can create strong perturbations in the ionosphere from pole to pole

Correspondence to:
P. R. Fagundes,
fagundes@univap.br

Citation:
Fagundes, P. R., L. P. Goncharenko, A. J. de Abreu, K. Venkatesh, M. Pezzopane, R. de Jesus, M. Gende, A. J. Coster, and V. G. Pillat (2015), Ionospheric response to the 2009 sudden stratospheric warming over the equatorial, low, and middle latitudes in the South American sector, *J. Geophys. Res. Space Physics*, *120*, doi:10.1002/2014JA020649.

Received 7 OCT 2014
Accepted 31 JUL 2015
Accepted article online 6 AUG 2015

Ionospheric response to the 2009 sudden stratospheric warming over the equatorial, low, and middle latitudes in the South American sector

P. R. Fagundes[1], L. P. Goncharenko[2], A. J. de Abreu[1], K. Venkatesh[1], M. Pezzopane[3], R. de Jesus[1], M. Gende[4], A. J. Coster[2], and V. G. Pillat[1]

[1]Física e Astronomia, Universidade do Vale do Paraíba (UNIVAP), São José dos Campos, São Paulo, Brazil, [2]MIT Haystack Observatory, Massachusetts Institute of Technology, Westford, Massachusetts, USA, [3]Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, [4]Facultad de Ciencias Astronomicas y Geofisicas, Universidad Nacional de La Plata, La Plata, Argentina

Abstract The present study investigates the ionospheric total electron content (TEC) and F-layer response in the Southern Hemisphere equatorial, low, and middle latitudes due to major sudden stratospheric warming (SSW) event, which took place during January–February 2009 in the Northern Hemisphere. In this study, using 17 ground-based dual frequency GPS stations and two ionosonde stations spanning latitudes from 2.8°N to 53.8°S, longitudes from 36.7°W to 67.8°W over the South American sector, it is observed that the ionosphere was significantly disturbed by the SSW event from the equator to the midlatitudes. During day of year 26 and 27 at 14:00 UT, the TEC was two times larger than that observed during average quiet days. The vertical TEC at all 17 GPS and two ionosonde stations shows significant deviations lasting for several days after the SSW temperature peak. Using one GPS station located at Rio Grande (53.8°S, 67.8°W, midlatitude South America sector), it is reported for the first time that the midlatitude in the Southern Hemisphere was disturbed by the SSW event in the Northern Hemisphere.

1. Introduction

The equatorial and low-latitude ionosphere/thermosphere system is predominantly disturbed by waves [gravity waves/Medium-scale Travelling Ionospheric Disturbances (MSTIDs), tides, and planetary waves (PWs)], which are generated in the lower atmosphere or in situ. These waves are strongly connected with the ionospheric day-to-day variability in the equatorial and low latitudes and are important topics of investigation. Considerable research has gone into understanding the physics behind the observed high variability, particularly in the F2 layer [*Fagundes et al.*, 2005, 2009; *Klausner et al.*, 2009; *MacDougall et al.*, 2009; *Rishbeth et al.*, 2009]. For many years, it was thought that during geomagnetic quiet conditions, the equatorial and low-latitude F2 layer was mainly perturbed by waves or electric fields generated by the equatorial electroject (EEJ), via tidal winds, which are transmitted along the magnetic field lines to equatorial F-region altitudes [*Fagundes et al.*, 2009]. In contrast, during geomagnetic disturbed periods, when energy sources are in the high latitudes, the traveling ionospheric disturbances (TIDs) travel a very long distance from the high latitude to the equatorial region. In addition, disturbed electric fields can be mapped via magnetic field lines, which, in turn, disturb the equatorial and low-latitude F layer [*Sahai et al.*, 2009; *de Abreu et al.*, 2010; *de Jesus et al.*, 2013].

The sudden stratospheric warming (SSW) is associated with a rapid increase of the stratosphere polar temperature during winter time. This meteorological phenomenon is characterized by disturbances in the interaction between the upward planetary wave and zonal wind. The zonal wind that normally propagates eastward during the winter time sometimes decelerates or even reverses to westward, and its interaction with planetary wave changes. As a result of this change in its interaction, the polar stratospheric temperature increases during several days. Recently, an unforeseen coupling between high latitudes, midlatitudes, and equatorial/low latitudes at upper atmospheric/ionospheric altitudes was discovered during sudden stratospheric warming (SSW) events [*Goncharenko and Zhang*, 2008; *Goncharenko et al.*, 2010a, 2010b, 2013a, 2013b; *Vineeth et al.*, 2009; *Chau et al.*, 2010, 2012; *Liu et al.*, 2011; *Pancheva and Mukhtarov*, 2011; *Bessarab et al.*, 2012; *Fang et al.*, 2012; *Korenkov et al.*, 2012; *Sripathi and Bhattacharyya*, 2012; *Sumod et al.*, 2012; *Olson et al.*, 2013; *Upadhayaya and Mahajan*, 2013; *Xiong et al.*, 2013; *Pedatella et al.*, 2014a, 2014b]. Therefore, various aspects involved behind the effects of SSW need to be explored in order to improve our knowledge about the Earth's atmosphere.

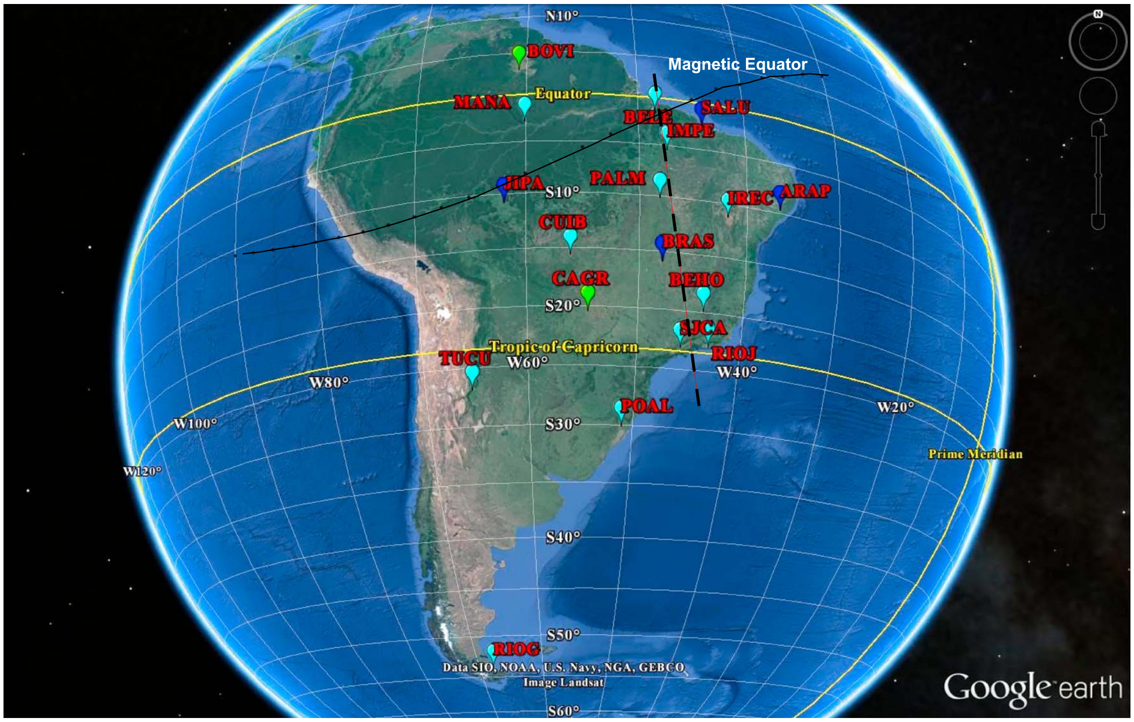

Figure 1. South American map showing the locations of GPS and Digital Ionosonde stations. The blue and green icons indicate stations that are analyzed in more detail. The GPS stations along the black colored dashed line are used to study the EIA characteristics during the present SSW event.

The ionospheric disturbances caused by SSW during the 2009 event have been studied in detail by many researchers. *Chau et al.* [2010, 2012] pointed out that the effects are most visible during the daytime. The strongest signatures are observed in the total electron content (TEC) measurements, the vertical drift was disturbed at the magnetic equator, and the electron and neutral densities showed disturbances. The TEC at tropical regions shows strong latitudinal dependence, with monotonic depletion at the dip equator and large hemisphere asymmetry [*Liu et al.*, 2011]. The equatorial electroject (EEJ) strength presents significant changes during SSW events [*Upadhayaya and Mahajan*, 2013]. In addition, the semidiurnal lunar tides in TEC and wind increase during the SSW event [*Xiong et al.*, 2013]. *Fejer et al.* [2010, 2011] showed that lunar semidiurnal tidal wave changes are the most likely source of the unusual ionospheric perturbations.

The present paper investigates the F2-layer response in the Southern Hemisphere equatorial, low, and middle latitudes due to major sudden stratospheric warming (SSW) event. Using the large database from 17 GPS receivers and two ionosonde stations spanning from 2.8°N to 53.81°S and 36.7°W to 67.8°W, the disturbances in the vertical total electron content (VTEC) caused from the equator to the midlatitudes during the SSW event were studied, and the results are presented. In addition, the variations in the equatorial ionization anomaly (EIA) were also studied.

2. Observations

In the present study, the stratospheric temperatures at 10 hPa (~30 km) between 60° and 90° on the Northern Hemisphere were obtained from the NASA online data service http://acdb-ext.gsfc.nasa.gov/Data_services/met/ann_data.html. The dual frequency GPS measurements from 17 receivers distributed from 2.8°N to 53.8°S latitudes and from 36.7°W to 67.8°W longitudes over the South American sector during the period from January to February 2009 were used. The GPS used in this study are Trimble, Leica, and Ashtec. These receivers are from the Instituto Brasileiro de Geografia e Estatistica (IBGE) network of GPS receivers (http://www.ibge.gov.br/home/geociencias/geodesia/rbmc/rbmc_est.php). The TEC values are derived using the differential delay technique using the dual frequency measurements at L1 and L2 frequencies over the considered locations. Simultaneous ionosonde measurements over the equatorial ionization anomaly (EIA) crest

Table 1. Details of the GPS and Digital Ionosonde Station Symbols, Latitudes, Longitudes, and Dip Latitude Sites Used in the Present Investigation

Station Name	Symbols	Geog. Lat (+N)	Geog. Lon (+W)	Dip. Lat
		GPS Stations		
Boa Vista	BOVI	2.8	60.7	10.2°N
Manaus	MANA	−3.0	60.1	4.7°N
Belem	BELE	−1.4	48.5	0.7°N
Ji-Parana	JIPA	−10.9	62.0	1.5°S
Sao Luis	SALU	−2.6	44.2	2.8°S
Imperatriz	IMPE	−5.5	47.5	3.5°S
Palmas	PALM	−10.9	48.2	7.8°S
Cuiaba	CUIB	−15.6	56.1	8.0°S
Irece	IREC	−11.2	41.9	11.7°S
Brasília	BRAS	−15.9	47.9	12.3°S
Campo Grande	CAGR	−20.4	54.5	12.7°S
Arapiaca	ARAP	−9.7	36.7	13.4°S
Belo Horizonte	BEHO	−19.9	43.9	17.8°S
S. J. Campos	SJCA	−23.2	45.9	19.2°S
Rio de Janeiro	RIOJ	−22.9	43.2	20.4°S
Porto Alegre	POAL	−30.1	51.1	21.5°S
Rio Grande	RIOG	−53.8	67.8	32.3°S
		Ionosonde Stations		
Tucuman	TUCU	−26.9	65.4	14.4°S
S. J. Campos	SJCA	−23.2	45.9	19.2°S

locations, Tucuman (TUCU) and Sao Jose dos Campos (SJCA), were also used to study the variations of the F-layer peak parameters during the considered SSW event. Figure 1 and Table 1 show the geographical and dip latitude locations of all these GPS and ionosonde receivers over the South American sector. The ionosonde at SJCA is the Canadian Digital Ionosonde, and the ionosonde at TUCU is Advanced Ionospheric Sounder. The ionograms over the two locations are scaled as per the procedure explained in *Piggott and Rawer* [1978].

3. Results

Figure 2 presents the average stratospheric temperatures from day of year (DOY) 1 to 55 in the Northern Hemisphere. This figure indicates that the stratospheric temperature at high latitude rapidly increases from 11 January 2009 (~200 K) to 23 January 2009 (~250 K). After reaching a peak on 23 January 2009, the temperature gradually decreases toward the end of February 2009, and then the temperature reaches the typical quiet day value of nearly ~210 K. During this SSW event, the solar activity was very low (F10.7 ~ 68 W/m^2 Hz) and geomagnetic conditions are very quiet. The minimum Dst in January and February is around −29 nT and −38 nT, respectively (http://wdc.kugi.kyoto-u.ac.jp/dstdir). Hence, any ionospheric disturbance, in the equatorial, low-latitude, and midlatitude regions, during these 2 months is not related to geomagnetic activity and could be due to the effect of the SSW. The following sections describe the response of the equatorial, low, and midlatitude ionosphere during the considered SSW event.

3.1. VTEC at Equatorial and Low Latitudes

Figure 3a presents the VTEC variations as a function of time (UT) and day of year (DOY) from January to February 2009 at Sao Jose dos Campos (23°S, under EIA crest location). The white solid line shows the average stratospheric temperature variation between 60°N and 90°N at 10 hPa (~30 km), and vertical dashed lines indicate the disturbed days (DOY 23–27) due to the SSW. In order to avoid high-frequency changes and ripples in VTEC, the 2 h running average values have been calculated and presented.

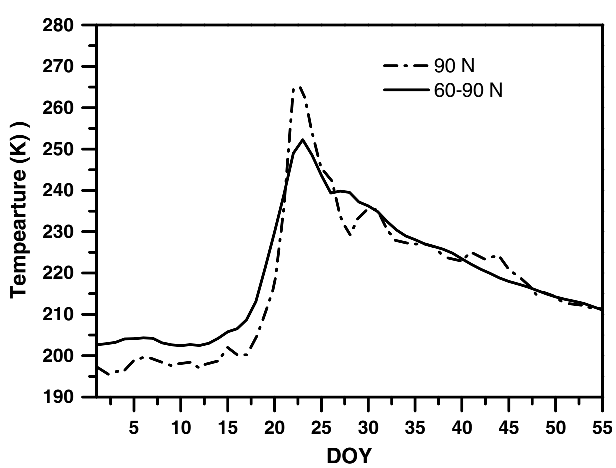

Figure 2. Plots showing the stratospheric temperatures at 90°N and 60°–90°N (averaged) at 10 hPa (~30 km) in the Northern Hemisphere during the period January–February 2009.

The diurnal variations of VTEC over the low latitude stations during DOY 23 and 24 are presented in Figure 3b, and those during DOY 25, 26, and 27 are presented in Figure 3c. The mean diurnal variations of VTEC during 10 quiet days (the days without SSW, i.e., from DOY 1 to 10) in the considered period are plotted as gray bands in

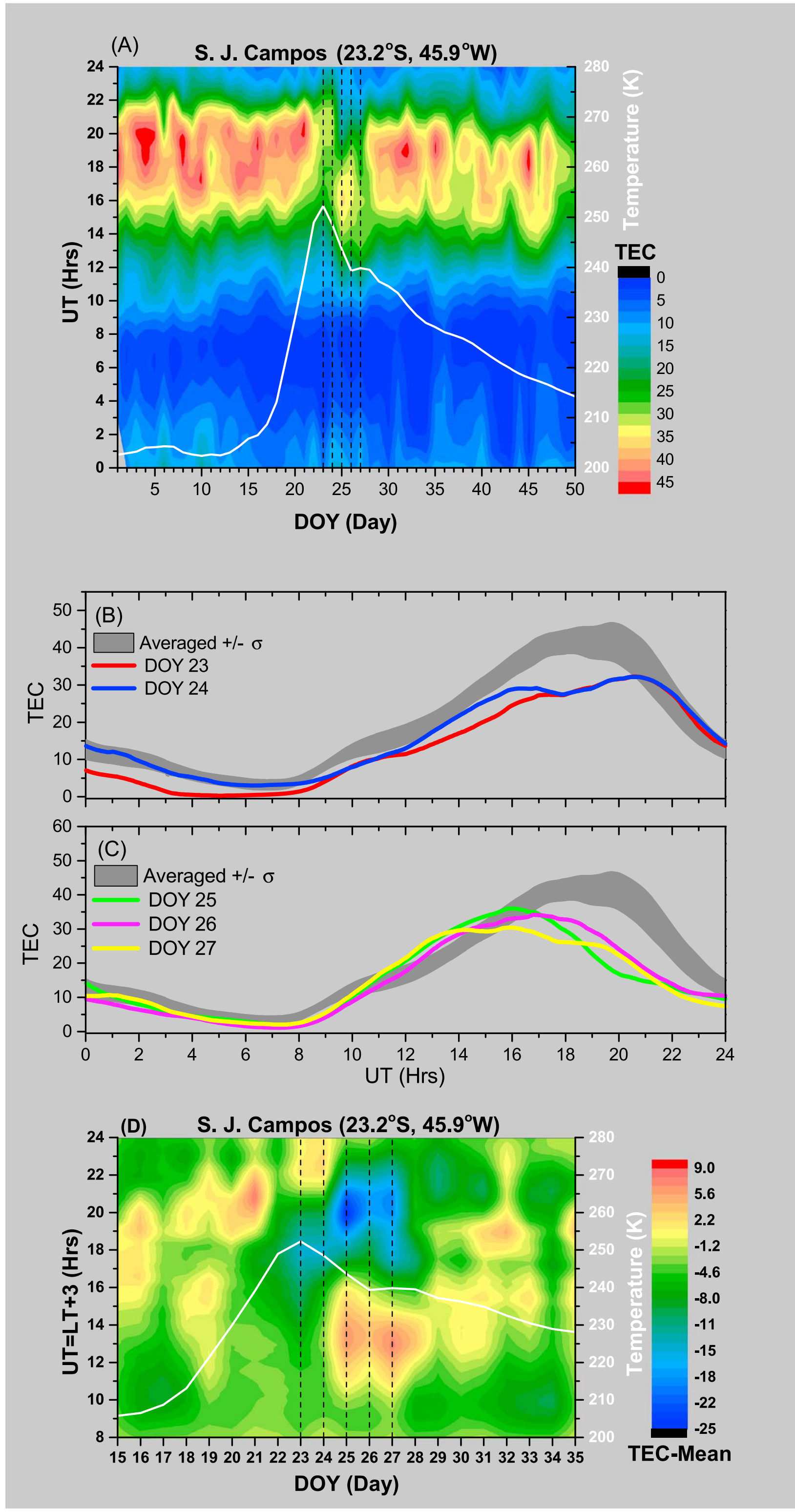

Figure 3. (a) Contour plot showing the VTEC variations with UT as a function of DOY (January–February 2009) at Sao Jose dos Campos (23°S, near the EIA crest). The white solid line shows the average stratospheric temperature variations from 60°N to 90°N at 10 hPa (~30 km), and the dashed lines indicate the DOY from 23 to 27. (b) The VTEC diurnal variations during disturbed days (DOY 23 and 24). The averaged quiet day VTEC is shown as gray bands with the band widths indicating ±1 standard deviation. (c) The same as Figure 3b but for DOY 25, 26, and 27. (d) Variations of the TEC deviation from the mean during 08 to 24 UT (05 to 21 LT) for DOY 15 to 35.

Figures 3b and 3c, and the width of this gray band represents the ±1 standard deviation in VTEC values. The quiet day period was not affected by the SSW. The mean values showed in Figures 3b and 3c illustrate that during nighttime from 00:00 UT to 10:00 UT (21:00 to 07:00 LT), the VTEC varies around 2–15 TECu. After 10:00 UT (07:00 LT), the VTEC starts increasing with the increasing solar ionization and fountain effect and reaches a peak values between 40 and 47 TECu from 17:00 to 21:00 UT (14:00 to 18:00 LT). But before it starts decreasing, there is a faint kink around 20:00–21:00 UT (17:00–18:00 LT). This VTEC enhancement is due to the electric field prereversal enhancement that takes place just after the sunset, and it reinforces the EIA. It is important to mention that the effects of the electric field prereversal enhancement in the TEC, at low latitude, depend on season and solar cycle [for more details, see *Fejer et al*., 1979; *Fagundes et al*., 2009].

A comparison, between the diurnal variations of VTEC (DOY 23 to 27) over low latitudes with those of the quiet day average TEC (gray band), revealed that the VTEC values show significant disturbances, and the onset of the disturbance is coincident with the SSW peak (Figure 3). The contours in Figure 3a illustrate a significant depletion of the maximum daytime values of TEC during the SSW event. The maximum TEC observed on quiet days and during the ascending phase of stratospheric temperature occurs from 16:00 to 21:00 UT (red pattern—Figure 3a). However, after the stratospheric temperature reaches its highest value, the diurnal pattern in TEC variations change during the next 5 or 6 days (DOY 23 to 28). During these disturbed days, the red pattern (high TEC Values) disappeared, and it is possible to notice a weak yellow pattern (low TEC values). A similar result was reported by *Goncharenko et al*. [2010a, 2010b], who noticed that the low-latitude ionosphere perturbation persisted for several days after the SSW peak. Further, a time shift has also been observed in the day maximum behavior after the stratospheric temperature peak. This may be attributed to the variations in the equatorial dynamics during the SSW which may be leading to the occurrence of an early day maximum in the TEC variations over the anomaly crest locations.

Figure 3b shows that the diurnal variations of VTEC during DOY 23 and 24 are quite similar to those of the diurnal averaged quiet day variations (gray band). However, the daytime maximum values of VTEC during DOY 23 and 24 are lower than the quiet day averaged values from 08:00 UT to 21:00 UT (05:00 to 18:00 LT). The diurnal variation of TEC during quiet days shows the daytime TEC maximum around 45–50 TECu, while the daytime maximum during the SSW event is around 30–35 TECu, which indicates a significant decrease of about 35%.

The TEC values during the following 3 days from DOY 25 to 27 are compared with the quiet day diurnal average TEC variations (gray band) in Figure 3c. During these 3 days, the diurnal variations of TEC are not similar to the averaged quiet day variations. The main difference is in the occurrence of the day maximum TEC. The averaged quiet day reaches its maximum around 18:00 to 20:00 UT (15:00 to 17:00 LT) during the quiet days, while the diurnal variation of TEC during the SSW shows its maximum around 15:00 to 17:00 UT (12:00 to 14:00 LT). Nevertheless, on all three DOYs 25, 26, and 27 (11:00–16:00 UT to 8:00–13:00 LT), small enhancements are seen when compared to the quiet time behavior, which, however, decreases later (16:00–24:00 UT to 13:00–21:00 LT), by around 10 TECu. In Figure 3d are presented the deviations of TEC from the average variations during 8 to 24 UT for DOY 15 to 35. The depletion in day maximum TEC from 17 to 22 UT (14 to 19 LT) is clearly seen after the SSW occurrence during DOY 23 to 27. Further, this contour clearly indicates the early occurrence of day maximum between 10 and 16 UT (07 to 13 LT) from DOY 25 to 27.

Therefore, it is possible to conclude that the 2009 SSW event produced the following: (1) low-latitude ionospheric disturbances at the days of SSW temperature peak; (2) anomalous VTEC diurnal variation 2–4 days after its peak, showing depletions and enhancements as compared with averaged quiet days; and (3) significant depletion in comparison to enhancements in TEC. This result supports the previous studies reported by *Pancheva and Mukhtarov* [2011] and *Bessarab et al*. [2012].

During 2009, the solar activity was very low, and the VTEC from 24:00 UT to 11:00 UT in the morning was very low (VTEC < 15); considerable variations in VTEC are not observed during this time. However, after 12:00 UT when the VTEC increases, significant changes are observed due to the effect of the SSW. Hence, in order to highlight the VTEC changes during the 2009 SSW event, the VTEC variations with UT as a function of DOY from 09:00 UT to 24:00 UT at 16 different locations are presented in Figures 4a and 4b.

The contours presented in Figure 4 clearly indicate the SSW disturbance effect in VTEC, beginning in all 16 stations on DOY 23, just when the SSW reached its maximum temperature, and continuing for the next 5 to 6 days. Each station has its particular response to the SSW disturbances, with different strength and time

10.1002/2014JA020649

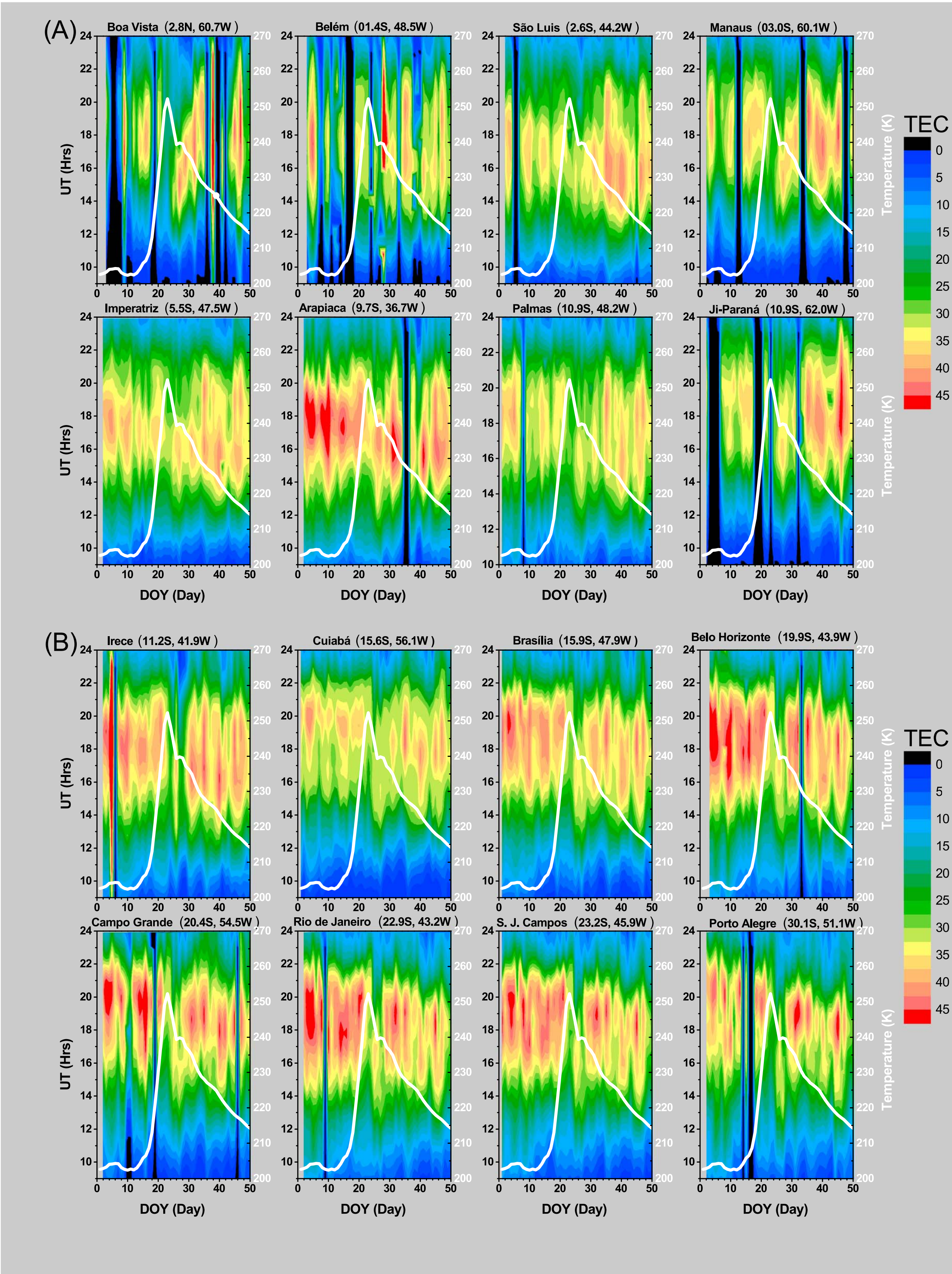

Figure 4. (a) VTEC variations with UT as a function of day of the year (January–February 2009) for eight stations over Brazilian sector, spanning from latitude 2.8°N to 10.9°S and longitude from 36.7°W to 62.0°W. (b) VTEC variation with UT as a function of day of the year (January–February 2009) for eight stations over Brazilian sector, spanning from latitude 11.2°S to 30.1°S and longitude 41.9°W to 56.1°W. The white solid lines show the averaged stratospheric temperature from 60°N to 90°N at 10 hPa (~30 km).

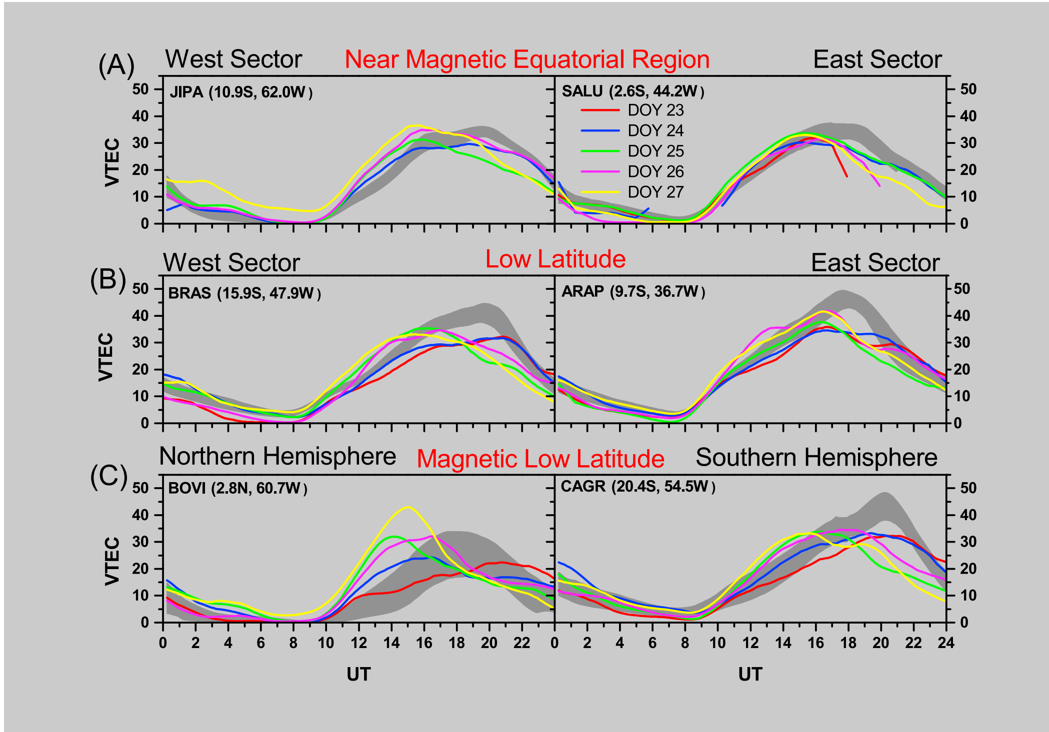

Figure 5. (a) The averaged quiet day diurnal VTEC variations are shown as gray bands with the band widths indicating ±1 standard deviation and the variation of VTEC during the disturbed period (DOY 23 to 27) over near magnetic equatorial region (Ji-Parana—JIPA and Sao Luis—SALU). (b) The same as Figure 5a but for low latitude (Brasilia—BRAS and Arapiaca—ARAP). (c) The same as Figure 5a but for Boa Vista (BOVI) located in the magnetic North Hemisphere and Campo Grande (CAGR) located in the South Hemisphere.

of duration. However, it is very clear that the VTEC was perturbed during 5 or 6 days in all 16 stations, which indicate that the SSW event in the Northern Hemisphere significantly influenced the electron density variations over the equatorial and low latitudes in the Southern Hemisphere. This result agrees with those presented by *Goncharenko et al*. [2010b].

The results presented in Figures 4a (equatorial stations) and 4b (low latitude stations) reveal that the VTEC disturbances during the SSW event are more prominent at low latitudes (particularly around the anomaly crest) compared to those at the equatorial region. In order to study these variations in more detail, TEC over six different stations is considered. Among these, two equatorial stations are considered at different longitudes, and the remaining stations are covering low-latitude and anomaly crests. Two low-latitude stations [Boa Vista (BOVI) and Campo Grande (CAGR)] are at the conjugate locations on either side of the magnetic equator on both hemispheres over the anomaly crests.

A significant portion of differences between different stations is most likely related to the location of the station with regard to the location of the equatorial ionization anomaly. Earlier studies have demonstrated that the largest variations in VTEC during SSW are observed at the crests of the EIA [*Goncharenko et al*., 2010a; *Liu et al*., 2011], and the location of the crests can vary periodically by several degrees in latitude [*Mo et al*., 2014]. In addition, the difference from one station to another is related with superimposed perturbation caused by MSTID and/or PW disturbances. Because the geographical extent covered by the 16 stations is very large, is 10.2°N to 32.3°S in dip latitude, and forms 36.7°W to 67.8°W in longitude, it is expected that the VTEC in each station is subject to different local sources of MSTIDs or close stations are subject to similar PW disturbances, but with different phases. The disturbance effects (SSW, MSTIDs, and PWs) are superimposed, but the effect of the SSW is very strong and global because the main feature of the disturbance is present in all 16 stations.

Figures 5a and 5b show the mean diurnal variations of TEC over two near magnetic equatorial stations and two low-latitude stations during the SSW event of DOY 23 to 27. The simultaneous quiet day mean values of TEC along with the ±1 standard deviations have been plotted as gray bands for comparison. The quiet days used to calculate the mean values and standard deviation are those days during which there is no SSW, i.e., from DOY 1 to 10. It is important to mention here that the two near equatorial stations [Ji-Parana (JIPA) and Sao Luis (SALU)] are separated by 18° in longitude and the two low-latitude stations [Brasília (BRAS) and Arapiaca (ARAP)] are separated by 11° in longitude. These stations are represented with blue-colored icon in Figure 1. In general, the quiet day VTEC variations over the equatorial and low latitudes show higher values in the afternoon hours. The diurnal variations of averaged quiet day TEC show the daytime maximum of about 45 TECu over the low latitudes, while it is less (around 35 TECu) over the equatorial regions. This is due to the well-known phenomena of the fountain effect under which the uplift of the equatorial F layer takes place and the plasma over the equator is carried to low latitudes causing an increase in the low-latitude electron density.

The diurnal variations of TEC during DOY 23 to 27 show that the equatorial regions are less affected by SSW compared to that of the low latitudes. However, a decrease in the TEC values is observed at both equatorial stations after 16:00 UT when compared with the quiet day average TEC variations. Prominent influence of SSW is observed over the low-latitude stations. The daytime maximum TEC observed during the disturbed days is broad, varying between 35 and 40 TECu, and it is much less than those of the quiet day, which vary between 45 and 50 TECu around 17:00 UT. A similar conclusion was made by *Pancheva and Mukhtarov* [2011].

Figure 5c shows the diurnal variations of VTEC at two magnetic low-latitude stations (BOVI and CACR), one in the Northern Hemisphere and another one in the Southern Hemisphere, which are separated by about 23° latitude. These stations are shown in Figure 1 with a green icon. A perusal of Figure 5c indicates that the VTEC in the Northern Hemisphere was more affected by the SSW than the VTEC in the Southern Hemisphere. The VTEC at the Northern Hemisphere (BOVI) was larger than the averaged quiet days from 10:00 UT to 16:00 UT on DOY 24, 25, 26, and 27 (before the VTEC reaches it maximum daily), and the averaged VTEC values of disturbed days (DOY 24, 25, 26, and 27) from 10:00 UT to 16:00 UT were 100% larger than the averaged quiet day. While at the Southern Hemisphere (CAGR), the VTEC was lower than the averaged quiet days from 18:00 UT to 24:00 UT (after the VTEC reach it maximum daily), and the averaged VTEC values of disturbed days from 18:00 to 24:00 were 60% lower than the averaged quiet day.

These hemispheric differences can be attributed to the reason that the SSW occurred in the high-latitude Northern Hemisphere. The strong latitudinal dependence and hemispheric asymmetry of the TEC disturbances observed in the present study during SSW are in agreement with those reported earlier by *Liu et al*. [2011]. However, the present study reveals the important characteristics such as latitudinal and hemispheric differences due to SSW events with quantitative database in the South American sector.

A perusal of Figures 3a and 3b indicates that the electron density at the anomaly crest locations in the South America sector was perturbed by the SSW event. In addition, *Goncharenko et al*. [2010a] recently reported that after the peak in stratospheric temperature, an enhancement of the EIA in the morning sector and a suppression of the EIA in the afternoon sector are observed. Also, *Liu et al*. [2011] showed that at the equatorial region, in the Asian sector, an overall drop of the TECu throughout the daytime occurs during the whole period from DOY 23 to DOY 31, with maximum depletion from DOY 26 to DOY 27, and, at low latitude, the TECu shows a morning enhancement and afternoon depletion in comparison to the quiet time. It appears that the American sector has a slice different response as compared with the Asian sector. Figure 5 shows that at equatorial region and low latitude, the TECu during disturbed days (DOY 23 to DOY 27) presents a similar value of quiet days during the morning and afternoon depletion, except for BOVI (Northern Hemisphere) that presented a morning enhancement and afternoon depletion.

Hence, in order to investigate the day-to-day variability in the formation of EIA before and during the SSW event, the TEC data from a chain of seven GPS receivers from the equator to the anomaly crest location and beyond along the common meridian of 45°W are considered. The stations used for this analysis [Belem (BELE), Imperatriz (IMPE), Palmas (PALM), BRAS, Belo Horizonte (BEHO), SJCA, and Porto Alegre (POAL)] are shown along the black colored dashed line in Figure 1. Contour plots showing the day-to-day variations of the EIA over the South American sector from DOY 10 to 29 are presented as a function of UT (LT = UT − 3 h) in Figure 6. In general, this figure illustrates that the EIA shows a significant variability from one day to the other.

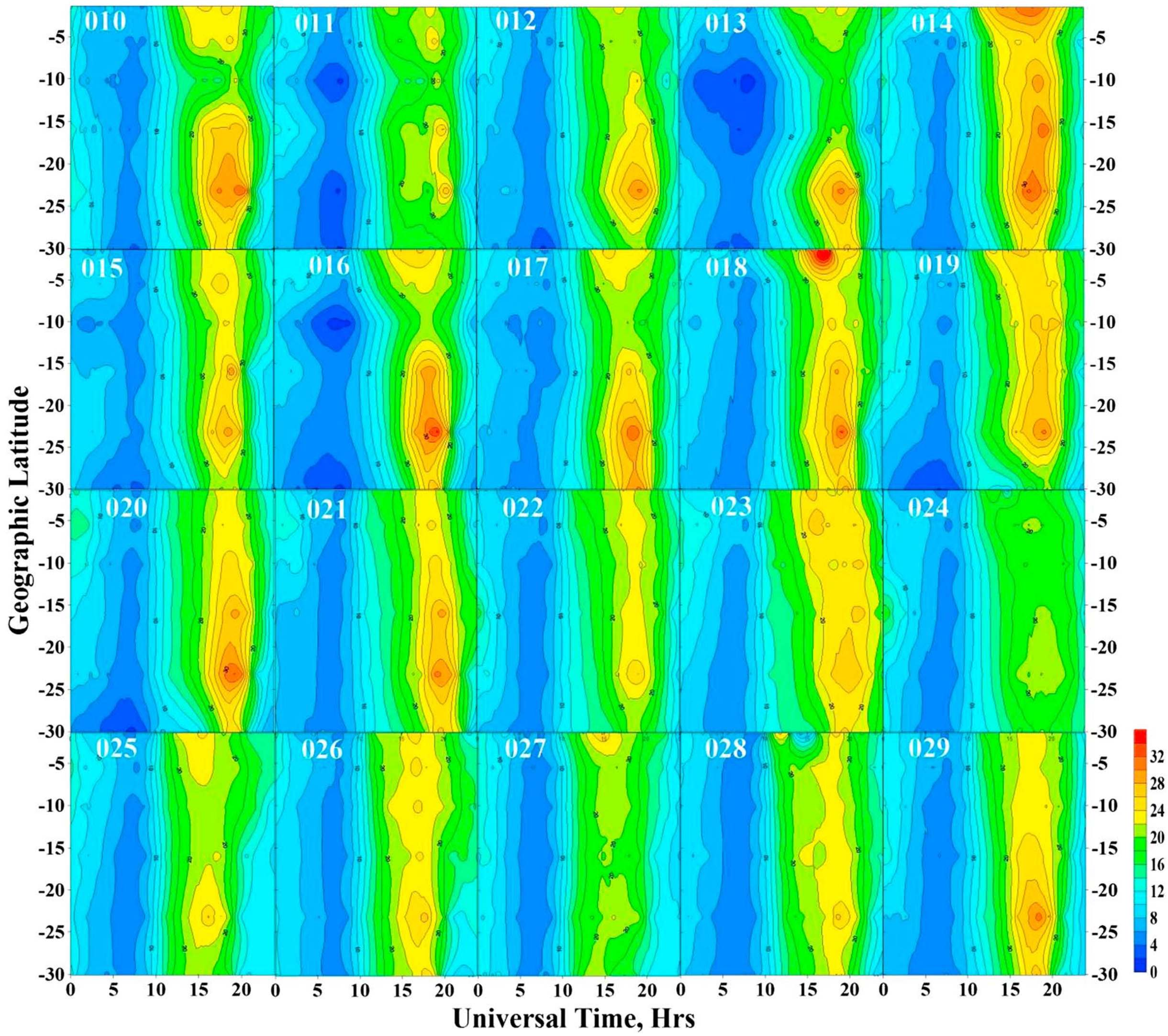

Figure 6. Contour plots showing the daily VTEC variation as a function of geographic latitude and UT (LT = UT − 3 h) from DOY 10 to DOY 29. The latitude starts from the equator to the EIA crest in the Southern Hemisphere and beyond.

The high variability of the EIA is expected, but the formation of the EIA is usually observed around 20°–25°S. But, the EIA variability during quiet days is related to the intensity of the EIA and the geographical position of the EIA crest. However, from DOY 22 to DOY 28, the EIA was perturbed, with perturbations seen as suppression of EIA lasting several days and shift of the daytime peak to earlier hours (in particular, on days 25–26). According to *Fejer et al*. [1979], the equatorial electric fields, which control the F-layer vertical drift, are the result of a complicated interaction between the E and F regions. The E-region dynamo fields are created by tidal winds in the E layer and are coupled to the F region via the nearly equipotential magnetic field lines. Because the EIA was suppressed for several days during the SSW, the changes in the EIA and the suppression of the anomaly observed in the present study during the SSW event can be produced by the changes in the E-region electric fields and tidal winds at E-region altitudes. *Paes et al*. [2014] and *Liu et al*. [2011] noticed an increase in the EIA intensity in the morning, followed by a decreased in the afternoon during SSW. Also, *Mo et al*. [2014] noticed a quasi 16 days periodic meridional movement of the EIA crest over China.

3.2. Ionosonde-Measured h′F and foF2 Variations at Low Latitude

Figure 7 shows the variations of h′F and foF2 during the SSW period (DOY 23 to 27) observed at TUCU (UT = LT + 4) and SJCA (UT = LT + 3). The diurnal variations of quiet day averaged values (+/− σ) of h′F (ionospheric F-region base height) and foF2 are shown as gray bands. A perusal of Figure 7 (left panels) indicates

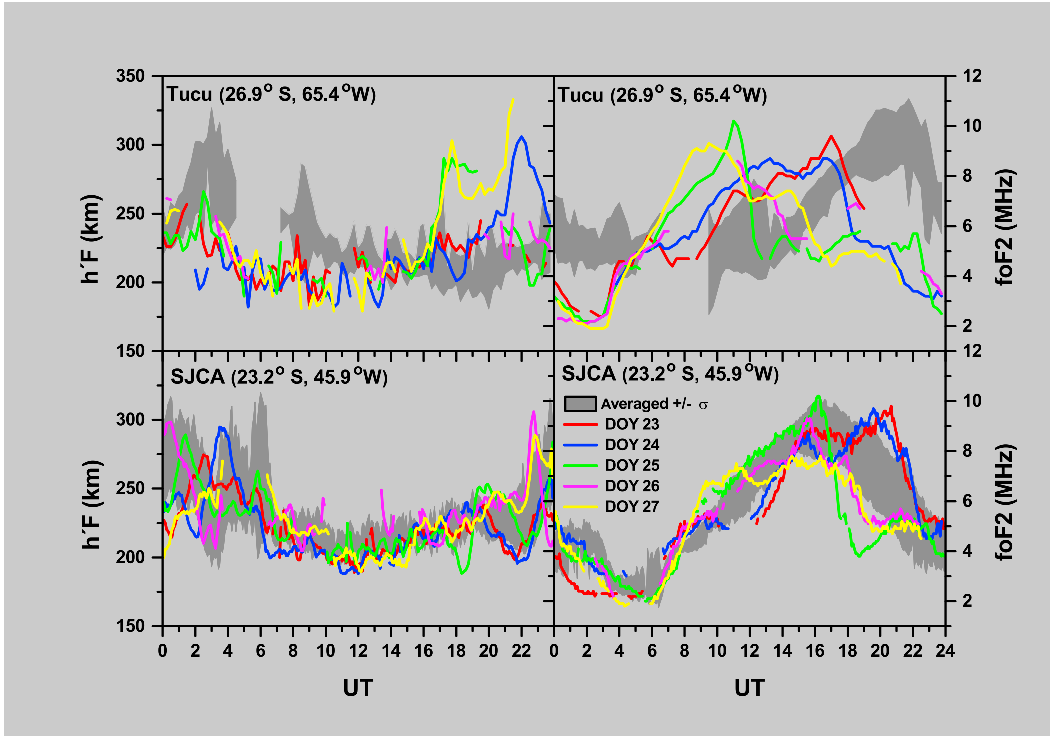

Figure 7. Variations of h′F and FoF2 during the period from DOY 23 to DOY 27 at Tucuman (TUCU) and Sao Jose dos Campos (SJCA). The averaged quiet day h′F and foF2 values are shown as gray bands with the band widths indicating ±1 standard deviation.

that, in general, the variations of h′F during the DOY 23 to 27 closely follow the quiet day averaged variations at both stations TUCU and SJCA, except over TUCU during some short intervals (DOY 24, 25 and 27), where an increase in the h′F up to 50–75 km is seen compared to that of the quiet day median values from ~18:00 to 24:00 UT. This increase is followed by a smaller decrease in h′F at 2–4 UT. *Sumod et al.* [2012] reported an increasing h′F in the evening hours (18:30 LT) over the Indian sector during the SSW of the January 2008 period. In addition, they pointed out that the strengthening of the prereversal enhancement may be associated with the SSW. In the present work, a similar behavior is noticed during DOY 24, 25, and 27 only in the American west sector (TUCU).

The foF2 presented in the right panels of Figure 7 from DOY 23 to 27 do not follow the quiet day averaged variations. The foF2 deviations from median values are stronger at TUCU than SJCA. This indicates strong east-west differences in the ionospheric response to the SSW event. Nevertheless, in both the stations, the SSW leads to a decrease and increase of foF2 compared with averaged quiet day variations. The decrease in foF2 occurs in the afternoon and evening/nighttime sector (16:00 UT to 04:00 UT) and reaches 2–6 MHz, while an increase of varying magnitude is observed mostly in the morning sector. The foF2 deviations from median values at TUCU are not only stronger than at SJC but also more positive. It can be explained by the fact that in quiet day, TUCU is located behind the crest of the equatorial ionization anomaly, and during SSW, this station may be located at the peak of the EIA crest. The observations in the South American sector are quite different than those observed in the Indian sector [*Sumod et al.*, 2012]. The present study carried out over the South American sector reveals strong foF2 disturbances compared with those of the quiet day variations, while these disturbances are weaker (~1 MHz) and not as long lasting in the Indian sector. It is not clear if stronger disturbances in the American longitudinal sector are related to the strength of the SSW event, which is more intense in January 2009 as compared to January 2008. *Upadhayaya and Mahajan* [2013] studied the variations of foF2 in the Asian sector and reported that there is an enhancement in the forenoon hours and depletion in the afternoon hours over Okinawa after the SSW event. The present observations over Tucuman are well in coincidence with the results over Okinawa, while the enhancement in the South American sector is found to be little stronger compared to the Asian sector. Other studies of the same events have

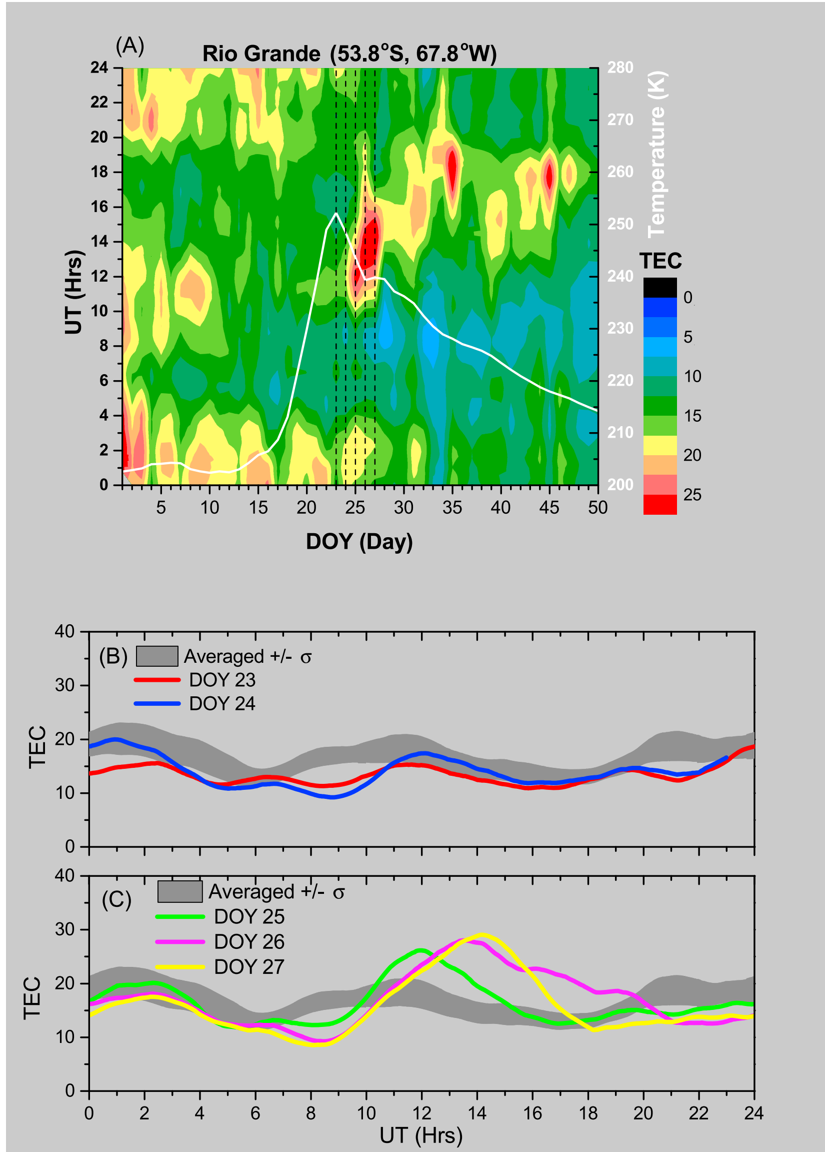

Figure 8. (a) VTEC variations with UT as a function of DOY (January–February, 2009) at Rio Grande (53.8°S, midlatitude, LT = UT − 4). The white solid line shows the average stratospheric temperature variation between 60°N and 90°N at 10 hPa (~30 km), and the dashed lines indicate the DOY from 23 to 27. (b) The averaged quiet day VTEC is shown as gray bands with the band widths indicating ±1 standard deviation and the variation of VTEC during the disturbed period of DOY 23 and 24. (c) The same as Figure 8b but for DOY 25, 26, and 27.

reported that ionospheric perturbations caused by SSW are stronger in the American sector than in the Asian sector for the January 2009 SSW event [*Goncharenko et al.*, 2010b; *Liu et al.*, 2011] and stronger than in the Asian and African sector for the January 2013 SSW event [*Goncharenko et al.*, 2013a]. The comparison of our observations with other results provides the additional evidence of significant longitudinal variations in the ionospheric response to SSW.

3.3. VTEC at Midlatitude

The results presented in previous sections indicated that the equatorial and low-latitude ionosphere in the Southern Hemisphere is significantly disturbed by the 2009 SSW event in the Northern Hemisphere. Because the disturbances reach up to the equatorial and low latitudes, some ionospheric coupling between low and middle latitudes should be expected. Therefore, the VTEC variations over Rio Grande (53.8°S, LT = UT − 4) have been studied to understand the midlatitude ionospheric response for the SSW event.

The contour plot presented in Figure 8a shows the day-to-day variations of VTEC as a function of DOY and UT, during January–February 2009 (summer season) in the Southern Hemisphere. It is readily observed from this figure that the VTEC is strongly disturbed during daytime (10:00 to 16:00 UT) for several days (DOY 24 to DOY 28). During this time, VTEC over Rio Grande increases almost by a factor of 2 (from 10–15 TECu to ~25 TECu). In addition, the disturbance lasts for several days after DOY 28 (DOY 29–36), although it becomes weaker and shifts to later local times.

The quiet day averaged diurnal variations of TEC are presented in Figures 8b and 8c as gray bands, and the thickness of these bands represents the ± standard deviation of VTEC. We note that quiet time VTEC at this time does not present strong day-to-night variations. The colored lines are the diurnal variation of the TEC during disturbed days (DOY 23 and 24 are in Figure 8b and DOY 25–27 are in Figure 8c). Comparing the VTEC variations during disturbed days with those of the averaged quiet day diurnal variation reveals that the disturbances are moderate on the DOY 23 and 24. The VTEC variations from DOY 25 to 27 show large deviations compared to the quiet day averaged variations, with daytime (13–16 UT) increase up to a factor of 2 (10–15 TECu) and nighttime-to-morning (7–9 UT) decrease by 5–7 TECu. These strong variations observed in the VTEC over Rio Grande are surprising because the SSW is in the Northern Hemisphere. For the strong variations to occur in the Southern Hemisphere, the influence SSW must have propagated up to the midlatitudes in the opposite (Southern) hemisphere. This highlights the importance of studying the changes in the ionosphere due to SSW in a broad range of latitudes, because single stratospheric events at high latitudes in the Northern Hemisphere disturb the whole ionosphere, suggesting that the SSW produces ionospheric perturbations from pole to pole. Therefore, it is very important to carry out observation and model simulation to study not only the ionosphere at midlatitude (South Hemisphere) but the neutral atmosphere because the neutral atmosphere may be the source of the ionosphere changes.

The simultaneous observations made from equatorial to low and middle latitudes reveal that after the SSW event, the day maximum TEC reduces and occurs at early hours (Figures 5a and 5b). The comparison of TEC variations in northern and southern low latitudes reveals that the day maximum TEC in the Northern Hemisphere increases after the SSW while it decreases in the Southern Hemisphere (Figure 5c). Further, at the midlatitudes, after the SSW event, the TEC exhibits a mixed trend of variation when compared to the average behavior. However, from DOY 25 to 27, a significant enhancement is observed in day maximum TEC.

4. Discussion and Conclusions

In the present investigation, VTEC measurements from dual frequency GPS receivers over 17 GPS locations covering a large geographical area from 2.8°N to 53.8°S latitudes and 36.7°W to 67.8°W longitudes in the South American sector have been used to study the ionospheric response to the January–February 2009 SSW event. The ionosonde measurements over two typical anomaly crest locations have also been used. The ionospheric responses at equatorial, low, and middle latitudes as well as the variability in the EIA characteristics during the 2009 SSW event are simultaneously investigated.

The results presented in this study clearly indicate that during the 2009 SSW event, there was a TEC depression during a few days, just after the SSW temperature peak (23 January 2009), as seen from the instruments located at low-latitude and equatorial region in South America. This is interesting and represents an additional contribution to the papers published up to now related to the 2009 SSW. The observed TEC depletion was not related with geomagnetic disturbances since this period was geomagnetically quiet. However, the negative phase during geomagnetic storms (decrease in the ionospheric electron density as compared with quiet periods) is related with change in composition of the neutral gas which increases the N_2/O ratio [*de Jesus et al*., 2013]. Therefore, a possible physical mechanism to explain the TEC depletion is the change in neutral composition that leads to an increase of the N_2/O ratio during the SSW since SSW is a large-scale meteorological process and it disturbs background wind, temperature, chemistry, and wave activity of middle atmosphere and vertical thermodynamics coupling in a large range of altitude and latitudes [*Fejer et al*., 2010]. *de Abreu et al*. [2014] investigated the propagation of planetary waves (PWs)/traveling planetary wave ionospheric disturbance (TPWIDs) from January 2009 to April 2010 at equatorial and low-latitude regions in the Brazilian sector. They noticed an equatorial and low-latitude coupling, via PWs/TPWIDs during the months of January–February 2009 and suggested that this may be related with the SSW. During the present SSW event, the TEC disturbance has some coincidence with the new moon day (DOY 26). But there is no such kind of disturbances during other full moon days (DOY 11 and 40), and hence, the observed variations in TEC should not be related to the lunar tide effects. However, more model simulation investigation must be done to improve our knowledge of the TEC depletion at equatorial and low latitudes during SSW.

The results observed in the present investigation are summarized below.

1. After the occurrence of the peak in the stratospheric temperature in the present 2009 SSW event, a large disturbance is observed at all of the 16 different locations from the equator to the low latitudes in the Southern Hemisphere. These disturbances are found to be retained for a long duration of about 5 to 6 days.
2. In general, the strength of the EIA crest shows large day-to-day variability, and the EIA is found to be suppressed during the SSW event.
3. The ionosonde-measured h′F and foF2 also show significant deviations from the mean quiet day variations. These deviations are largest in the afternoon-evening hours, reaching 50–70 km for h′F and 5–6 MHz for foF2. These American-longitude disturbances are found to be stronger than those reported by *Sumod et al*. [2012] in the Indian sector.
4. The VTEC variations in the southern midlatitudes (53.8°S, magnetic 43.6°S) also show significant disturbances during the present northern SSW event. This highlights the importance of the investigations on ionospheric response to the stratospheric warming because the SSW event in one hemisphere can create strong perturbations in the ionosphere from one pole to the other.
5. Simultaneous comparison of TEC variations from different latitudes reveals that after the SSW occurrence, the equatorial and low-latitude TEC show an early peak while the day maximum is decreasing in the Northern Hemisphere and increasing in the Southern Hemisphere. Over the midlatitudes, the day maximum TEC shows significant enhancement from DOY 25 to 27.

Acknowledgments
The authors thank the authorities of the “Rede Brasileira de Monitoramento Contínuo de GPS (RBMC)” operated by the “Instituto Brasileiro de Geografia e Estatística (IBGE),” Brazil, for kindly allowing us to use the data obtained by the RBMC (http://www.ibge.gov.br/home/geociencias/geodesia/rbmc/rbmc_est.php). The authors also thank the Brazilian funding agencies FAPESP grant 2012/08445-9, CNPq grants 302927/2013-1 and 457129/2012-3, and FINEP 01.100661-00 for the partial financial support.

Michael Liemohn thanks Arun Upadhayaya and Maxim Klimenko for their assistance in evaluating this paper.

References

Bessarab, F. S., Y. N. Korenkov, M. V. Klimenko, V. V. Klimenko, I. V. Karpov, K. G. Ratovsky, and M. A. Chernigovskaya (2012), Modeling the effect of sudden stratospheric warming within the thermosphere-ionosphere system, *J. Atmos. Sol. Terr. Phys.*, *90–91*, 77–85, doi:10.1016/j.jastp.2012.09.005.

Chau, J. L., N. A. Aponte, E. Cabassa, M. P. Sulzer, L. P. Goncharenko, and S. A. Gonzalez (2010), Quiet time ionospheric variability over Arecibo during sudden stratospheric warming events, *J. Geophys. Res.*, *115*, A00G06, doi:10.1029/2010JA015378.

Chau, J. L., L. P. Goncharenko, B. G. Fejer, and H. L. Liu (2012), Equatorial and low latitude ionospheric effects during sudden stratospheric warming events ionospheric effects during SSW events, *Space Sci. Rev.*, *168*(1–4), 385–417, doi:10.1007/s11214-011-9797-5.

de Abreu, A. J., et al. (2010), Hemispheric asymmetries in the ionospheric response observed in the American sector during an intense geomagnetic storm, *J. Geophys. Res.*, *115*, A12312, doi:10.1029/2010JA015661.

de Abreu, A. J., P. R. Fagundes, M. J. A. Bolzan, R. de Jesus, V. G. Pillat, J. R. Abalde, and W. L. C. Lima (2014), The role of the traveling planetary wave ionospheric disturbances on the equatorial F region post-sunset height rise during the last extreme low solar activity and comparison with high solar activity, *J. Atmos. Sol. Terr. Phys.*, *113*, 47–57.

de Jesus, R., Y. Sahai, P. R. Fagundes, A. J. de Abreu, C. Brunini, M. Gende, J. A. Bittencourt, J. R. Abalde, and V. G. Pillat (2013), Response of equatorial, low- and mid-latitude F-region in the American sector during the intense geomagnetic storm on 24–25 October 2011, *Adv. Space Res.*, *52*(1), 147–157, doi:10.1016/j.asr.2013.03.017.

Fagundes, P. R., V. G. Pillat, M. J. A. Bolzan, Y. Sahai, F. Becker-Guedes, J. R. Abalde, S. L. Aranha, and J. A. Bittencourt (2005), Observations of F layer electron density profiles modulated by planetary wave type oscillations in the equatorial ionospheric anomaly region, *J. Geophys. Res.*, *A12*, A12302, doi:10.1029/2009JA014390.

Fagundes, P. R., J. A. Bittencourt, J. R. Abalde, Y. Sahai, M. J. A. Bolzan, V. G. Pillat, and W. L. C. Lima (2009), F layer postsunset height rise due to electric field prereversal enhancement: 1. Traveling planetary wave ionospheric disturbance effects, *J. Geophys. Res.*, *114*, A12321, doi:10.1029/2009JA014390.

Fang, T. W., T. Fuller-Rowell, R. Akmaev, F. Wu, H. J. Wang, and D. Anderson (2012), Longitudinal variation of ionospheric vertical drifts during the 2009 sudden stratospheric warming, *J. Geophys. Res.*, *117*, A03324, doi:10.1029/2011JA017348.

Fejer, B. G., D. T. Farley, R. F. Woodman, and C. Calderon (1979), Dependence of equatorial F-region vertical drifts on season and solar-cycle, *J. Geophys. Res.*, *84*(A10), 5792–5796, doi:10.1029/JA084iA10p05792.

Fejer, B. G., M. E. Olson, J. L. Chau, C. Stolle, H. Lühr, L. P. Goncharenko, K. Yumoto, and T. Nagatsuma (2010), Lunar-dependent equatorial ionospheric electrodynamic effects during sudden stratospheric warmings, *J. Geophys. Res.*, *115*, A00G03, doi:10.1029/2010JA015273.

Fejer, B. G., B. D. Tracy, M. E. Olson, and J. L. Chau (2011), Enhanced lunar semidiurnal equatorial vertical plasma drifts during sudden stratospheric warmings, *Geophys. Res. Lett.*, *38*, L21104, doi:10.1029/2011GL049788.

Goncharenko, L., and S. R. Zhang (2008), Ionospheric signatures of sudden stratospheric warming: Ion temperature at middle latitude, *Geophys. Res. Lett.*, *35*, L21103, doi:10.1029/2008GL035684.

Goncharenko, L., J. L. Chau, P. Condor, A. Coster, and L. Benkevitch (2013a), 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.

Goncharenko, L. P., A. J. Coster, J. L. Chau, and C. E. Valladares (2010a), Impact of sudden stratospheric warmings on equatorial ionization anomaly, *J. Geophys. Res.*, *115*, A00G07, doi:10.1029/2010JA015400.

Goncharenko, L. P., J. L. Chau, H. L. Liu, and A. J. Coster (2010b), Unexpected connections between the stratosphere and ionosphere, *Geophys. Res. Lett.*, *37*, L10101, doi:10.1029/2010GL043125.

Goncharenko, L. P., V. W. Hsu, C. G. M. Brum, S. R. Zhang, and J. T. Fentzke (2013b), Wave signatures in the midlatitude ionosphere during a sudden stratospheric warming of January 2010, *J. Geophys. Res. Space Physics*, *118*, 472–487, doi:10.1029/2012JA018251.

Klausner, V., P. R. Fagundes, Y. Sahai, C. M. Wrasse, V. G. Pillat, and F. Becker-Guedes (2009), Observations of GW/TID oscillations in the F2 layer at low latitude during high and low solar activity, geomagnetic quiet and disturbed periods, *J. Geophys. Res.*, *114*, A02313, doi:10.1029/2008JA013448.

Korenkov, Y. N., et al. (2012), The global thermospheric and ionospheric response to the 2008 minor sudden stratospheric warming event, *J. Geophys. Res.*, *117*, A10309, doi:10.1029/2012JA018018.

Liu, H. X., M. Yamamoto, S. T. Ram, T. Tsugawa, Y. Otsuka, C. Stolle, E. Doornbos, K. Yumoto, and T. Nagatsuma (2011), Equatorial electrodynamics and neutral background in the Asian sector during the 2009 stratospheric sudden warming, *J. Geophys. Res.*, *116*, A08308, doi:10.1029/2011JA016607.

MacDougall, J., M. A. Abdu, I. Batista, P. R. Fagundes, Y. Sahai, and P. T. Jayachandran (2009), On the production of traveling ionospheric disturbances by atmospheric gravity waves, *J. Geophys. Res.*, *71*, doi:10.1016/j.jastp.2009.09.006.

Mo, X. H., D. H. Zhang, L. P. Goncharenko, Y. Q. Hao, and Z. Xiao (2014), Quasi-16-day periodic meridional movement of the equatorial ionization anomaly, *Ann. Geophys.*, *32*, 121–131, doi:10.5194/angeo-32-121-2014.

Olson, M. E., B. G. Fejer, C. Stolle, H. Luhr, and J. L. Chau (2013), Equatorial ionospheric electrodynamic perturbations during Southern Hemisphere stratospheric warming events, *J. Geophys. Res. Space Physics*, *118*, 1190–1195, doi:10.1002/jgra.50142.

Paes, R. R., I. S. Batista, C. M. N. Candido, O. F. Jonah, and P. C. P. Santos (2014), Equatorial ionization anomaly variability over the Brazilian region during boreal sudden stratospheric warming events, *J. Geophys. Res. Space Physics*, *119*, 7649–7664, doi:10.1002/2014JA019968.

Pancheva, D., and P. Mukhtarov (2011), Stratospheric warmings: The atmosphere ionosphere coupling paradigm, *J. Atmos. Sol. Terr. Phys.*, *73*(13), 1697–1702, doi:10.1016/j.jastp.2011.03.006.

Pedatella, N. M., H. L. Liu, F. Sassi, J. Lei, J. L. Chau, and X. Zhang (2014a), Ionosphere variability during the 2009 SSW: Influence of the lunar semidiurnal tide and mechanisms producing electron density variability, *J. Geophys. Res. Space Physics*, *119*, 3828–3843, doi:10.1002/2014JA019849.

Pedatella, N. M., et al. (2014b), The neutral dynamics during the 2009 sudden stratosphere warming simulated by different whole atmosphere models, *J. Geophys. Res. Space Physics*, *119*, 1306–1324, doi:10.1002/2013JA019421.

Piggott, W. R., and K. Rawer (1978), URSI handbook of ionogram interpretation and reduction—Report UAG-23A World Data Cent. A for Sol. Terr. Phys., Boulder, Colo.

Rishbeth, H., M. Mendillo, J. Wroten, and R. G. Roble (2009), Day-by-day modelling of the ionospheric F2-layer for year 2002, *J. Atmos. Sol. Terr. Phys.*, *71*(8), 848–856.

Sahai, Y., et al. (2009), Observations of the F-region ionospheric irregularities in the South American sector during the October 2003 'Halloween Storms', *Ann. Geophys.*, *27*(12), 4463–4477.

Sripathi, S., and A. Bhattacharyya (2012), Quiet time variability of the GPS TEC and EEJ strength over Indian region associated with major sudden stratospheric warming events during 2005/2006, *J. Geophys. Res.*, *117*, A05305, doi:10.1029/2011JA017103.

Sumod, S. G., T. K. Pant, L. Jose, M. M. Hossain, and K. K. Kumar (2012), Signatures of sudden stratospheric warming on the equatorial ionosphere-thermosphere system, *Planet. Space Sci.*, *63–64*, 49–55, doi:10.1016/j.pss.2011.08.005.

Upadhayaya, A. K., and K. K. Mahajan (2013), Ionospheric F2 region: Variability and sudden stratospheric warmings, *J. Geophys. Res. Space Physics*, *118*, 6736–6750, doi:10.1002/jgra.50570.

Vineeth, C., T. K. Pant, and R. Sridharan (2009), Equatorial counter electrojets and polar stratospheric sudden warmings—A classical example of high latitude-low latitude coupling?, *Ann. Geophys.*, *27*(8), 3147–3153.

Xiong, J. G., W. X. Wan, F. Ding, L. B. Liu, B. Q. Ning, and X. J. Niu (2013), Coupling between mesosphere and ionosphere over Beijing through semidiurnal tides during the 2009 sudden stratospheric warming, *J. Geophys. Res. Space Physics*, *118*, 2511–2521, doi:10.1002/jgra.50280.