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

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Abstract

The present study investigates the consequences of vertical coupling from lower to the upper atmosphere in the equatorial and low-latitude ionosphere in Southern Hemisphere during a major SSW event, which took place during January-February 2009 in the Northern Hemisphere. Using seventeen ground-based dual-frequency GPS stations and two ionosonde stations spanning from latitude 2.8^{o}N to 53.8^{o}S and from longitude 36.7^{o}W to 67.8^{o}W over the South American sector, it has been

observed that the ionosphere was significantly disturbed by the SSW event from Equator to the mid-latitudes. Using one GPS station located at Rio Grande (53.8^{o}S, 67.8^{o}W, mid-latitude-South America sector) it is reported for the first time that the mid-latitude in southern hemisphere was disturbed by the SSW event in the Northern hemisphere. For instance, during DOY 26 and 27 at 14:00 UT the TEC were twice larger than those observed during averaged quiet days. The VTEC at all 17 GPS and two ionosonde stations show significant deviations lasting for several days after the SSW temperature peak.

1. Introduction

The equatorial and low-latitude ionosphere/thermosphere system is predominantly disturbed by waves (MSTIDs, tides, and planetary waves), which are generated in the lower atmosphere or in-situ, as well as electric fields and TIDs produced by geomagnetic storm and UV, EUV, and X-ray solar radiation. For many years, it was thought that, during geomagnetic quiet conditions, the equatorial and low-latitude F-layer was mainly perturbed by waves that were generated not far away from the observed location or electric fields generated by the Equatorial Electroject (EEJ). On the contrary, during geomagnetic storms when the energy sources are in high latitudes the waves (TIDs) travel a very long distance from high latitude to equatorial region and electric fields can be mapped via magnetic field lines. However, in the recent times an unexpected coupling between high latitude, mid- latitude, and equatorial/low latitudes was discovered during sudden stratospheric warming (SSW) events. All aspects involved in this process must be explored in order to improve our knowledge about the Earth´s atmosphere.

The day-to-day variability in the equatorial and low-latitude ionosphere/thermosphere is one of highlighted topics of this investigation and considerable research has gone into understanding the physics behind the observed high variability, particularly in the F-layer (Rishbeth et al., 2009; Fagundes et al., 2009). It is well known that equatorial and low-latitude ionosphere/thermosphere system is predominantly disturbed by waves (gravity waves/ Medium-Scale Traveling Ionospheric Disturbances (MSTIDs), tides and planetary waves) that are generated in the lower atmosphere or in-situ (Fagundes et al., 2005, 2009; MacDougall et al., 2009; Klausner et al., 2009), solar radiation (UV, EUV and X-ray) and sometimes by disturbed electric fields and TIDs (Travelling Ionospheric Disturbances) generated during geomagnetic storms (Sahai et al., 2009; de Abreu et al., 2010; de Jesus et al., 2013).

For several years, it was thought that, during geomagnetically quiet conditions the equatorial and low-latitude F-layer was primarily perturbed either by waves that were generated not far away from the observed location or by electric fields generated from 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 storms when energy sources are in the high latitudes, the waves (TIDs) travel a very long distance from the high latitude to the equatorial region and disturbed electric fields can be mapped via magnetic field lines and, in turn, disturb the equatorial and low-latitude F-layer (de Abreu et al., 2010).

Recently an unforeseen coupling between high latitudes, mid latitudes, and equatorial/low latitudes at upper atmospheric/ionospheric altitudes was discovered during sudden stratospheric warming (SSW) events (Chau et al., 2010, Goncharenko et al., 2010a, 2010b). Interestingly, Resmi et al., (2013) have reported a coupling between polar and tropical stratosphere during SSW. They have further reported the presence of a strong cooling in the entire tropics (30^{o}N–30^{o}S) associated with SSW events and the cooling became intense of the order of 10–15^{o}C during the peak phase of the SSW. The exploration of all aspects involved in this process must be investigated in order to improve our knowledge of the Earth´s upper atmosphere and ionosphere.

The present paper investigates the effects of the lower-upper atmosphere vertical coupling at high latitude (Northern Hemisphere) on the equatorial, low- and mid-latitude ionosphere (Southern Hemisphere), during a major SSW, which took place in January-February 2009. Although the effect of the SSW on the ionosphere/upper atmosphere has been studied by several researchers (Chau et al., 2010, 2012, Goncharenko et al., 2010a, 2010b, 2013a, 2013b; Liu et al., 2011; Pancheva and Mukhtarov 2011; Bessarab et al., 2012; Korenkov et al., 2012), in this investigation, the effects of the 2009 SSW in the South American sector have been explored in more detail.

Using the large database from 17 GPS receivers and 2 ionosonde stations spanning form 2.8^{0}N to 53.81^{0}S and 36.7^{0}W to 67.8^{0}W over the South American

sector, the disturbances in the vertical Total Electron Content (VTEC) caused from equator to the mid-latitudes during the SSW event have been studied and the results are presented. Further, the variations in the Equatorial Ionization Anomaly (EIA) have been studied.

2. Observations

In the present study, the stratospheric temperatures at 10hPa (~30km) between 60^0 and 90^0 on the northern hemisphere have been 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^oN to 53.8^oS latitudes and from 36.7^oW to 67.8^oW longitudes over the South American sector during the period from January to February 2009 have been used. These receivers are from the network of 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 locations, Tucuman (TUCU) and Sao Jose dos Campos (SJCA) have also been 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 geomagnetic locations of all these GPS and ionosonde receivers over the South American sector.

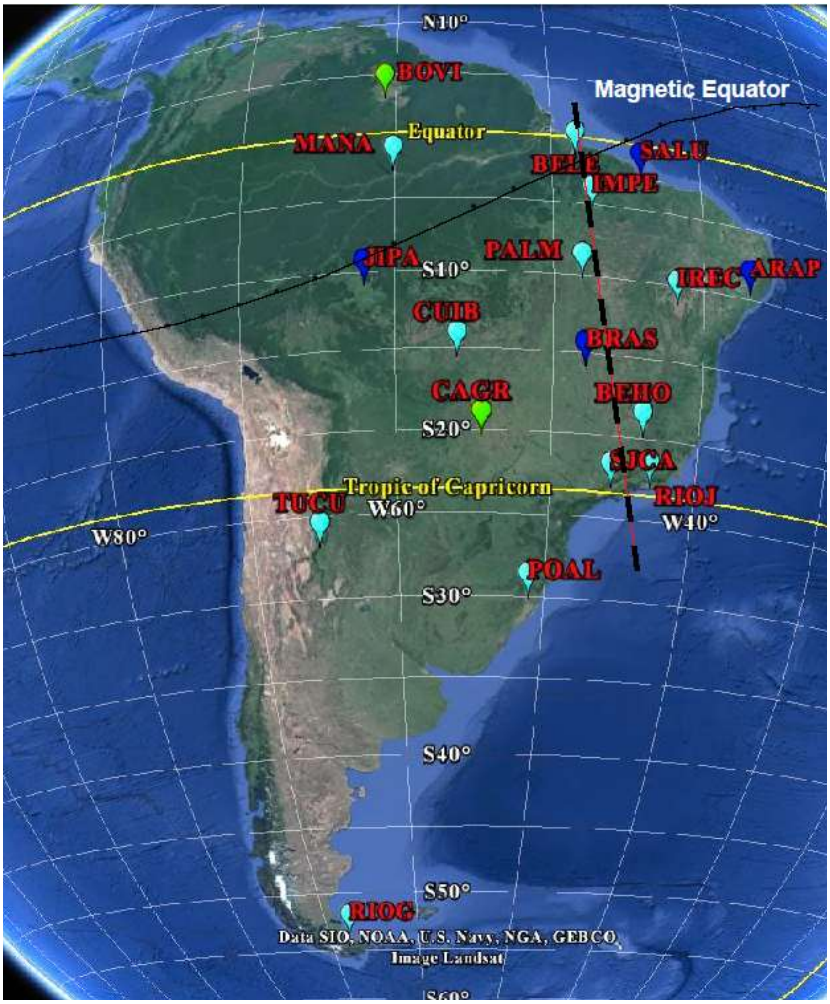

Figure 1. South American map showing the locations of GPS and Digital Ionosonde stations. The blue and green icons indicate stations that are analyzed in more details. The GPS stations along the black colored dashed line are used to study the EIA characteristics during the present SSW event.

131 **Table 1-** Details of the GPS and digital ionosonde stations symbols, latitudes and

132 longitudes sites used in the present investigation.

Site	Lat. Geog. +N	Lon. Geog. W	Lat. Mag. +N	Lon. Mag E
GPS stations				
Boa Vista - BOVI	2.8	60.7	12.6	11.7
Belem - BELE	-1.4	48.5	7.8	23.9
São Luis - SALU	-2.6	44.2	6.3	28.1
Manaus - MANA	-3.0	60.1	12.8	12.3
Imperatriz - INPE	-5.5	47.5	3.7	24.6
Arapiaca - ARAP	-9.7	36.7	-1.4	34.9
Palmas - PALM	-10.2	48.2	-1.4	23.5
Ji-Paraná - JIPA	-10.9	62.0	-0.9	10.0
Irece - IREC	-11.2	41.9	-2.4	29.6
Cuiabá - CUIB	-15.6	56.1	-5.8	15.5
Brasília - BRAS	-15.9	47.9	-6.6	23.4
Belo Horizonte - BEHO	-19.9	43.9	-10.9	27.0
Campo Grande - CACR	-20.4	54.5	-10.7	16.8
Rio de Janeiro - RIOJ	-22.9	43.2	-13.9	27.4
S. J. Campos - SJCA	-23.2	45.9	-14.0	24.8
Porto Alegre - POAL	-30.1	51.1	-20.5	19.4
Rio Grande - RIOG	-53.8	67.8	-43.6	3.6
Ionosonde stations				

S. J. Campos - SJCA	-23.2	45.9	-14.6	24.7
Tucumán - TUCU	-26.9	65.4	-16.8	6.2

3. Results and Discussion

Figure 2 presents the average stratospheric temperatures from day 1 to 55 in the northern hemisphere. It is seen from this figure that the stratospheric temperature at high latitude rapidly increases from January 11, 2009 (~200 K) to January 23, 2009 (~250 K). After reaching a peak on 23rd January, 2009, the temperature gradually decreases towards the end of February 28, 2009 and 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 and the minimum Dst on January and February is around -29 nT and -38 nT respectively. Hence, any ionospheric disturbance, in the equatorial and low- and mid-latitude regions, during these 2 months are not related to geomagnetic activity and could be due the effect of the SSW. The following sections describe the response of the equatorial, low and mid latitude ionosphere during the considered SSW event.

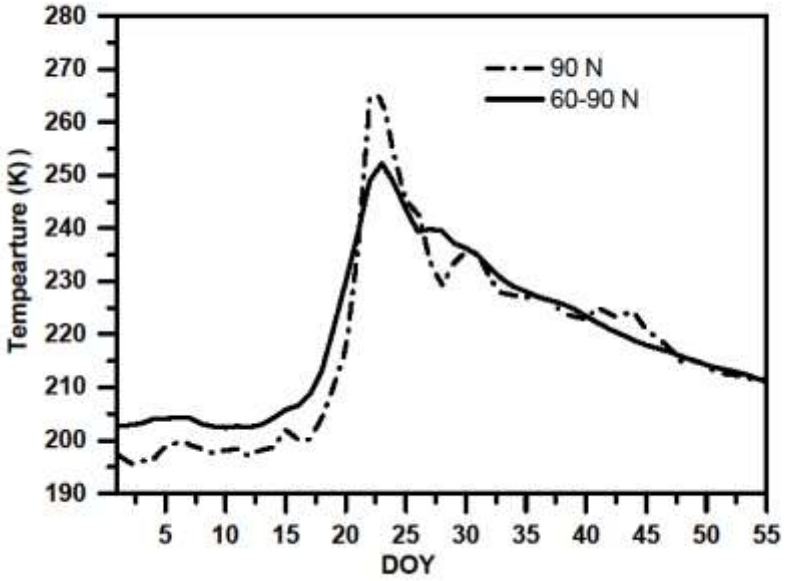

Figure 2. Plots showing the stratospheric temperatures at 90^{o}N and 60^{o}-90^{o}N (averaged) at 10 hPa (~30 km) in the northern hemisphere during the period January-February, 2009.

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^{o}S, an EIA crest location). The white solid line shows the average stratospheric temperature variation between 60^{o}N to 90^{o}N at 10hPa (~30km) 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 two hours running average values have been calculated and presented.

164 The diurnal variations of VTEC over the low latitude stations during DOY 23,
165 24 are presented in Figure 3B and during DOY 25, 26 and 27 are presented in
166 Figure 3C. The mean diurnal variations of VTEC during 10 quiet days in the
167 considered period are plotted as gray bands in Figure 3B and C and the width of
168 this gray band represents the ± 1 standard deviation in VTEC values. It could be
169 mentioned here that the quiet day period was not affected by the SSW. It is seen
170 from this Figure that, during nighttime from 00:00 UT to 10:00 UT (21:00 to 07:00
171 LT) the VTEC varies around 2-15 TECu. After 10:00 UT (07:00 LT) the VTEC start
172 increasing due to solar radiation and fountain effect and reach a peak value of ~45
173 TECu around 17:00 UT (14:00 LT) and then start decreasing while a secondary
174 peak is observed around 20:00 - 21:00 UT (17:00 - 18:00 LT). This second VTEC
175 peak is due to the electric field pre-reversal enhancement that takes place just after
176 the sunset and its reinforce the EIA. It is important mention that the effects of the
177 electric field pre-reversal enhancement in the TEC, at low latitude, depend on
178 season and solar cycle (for more details see Fagundes et al., 2009 and Fejer et al.,
179 1979).
180
181 A comparison between the diurnal variations of VTEC over low latitudes with
182 those of the quiet day averaged TEC (gray band), revealed that the VTEC values
183 show significant disturbances and the onset of the disturbance is coincident with
184 the SSW peak (Figure 3). It is seen from the contours presented in Figure 3A that
185 there is a significant decrease of the maximum daytime values of TEC during the
186 SSW event. The day maximum is observed around 16:00 UT during the SSW while
187 the peak is observed between 18:00 and 20:00 UT in the remaining days. A similar

result has been reported by Goncharenko et al. (2010a) and (2010b); they noticed that the low-latitude ionosphere perturbation persisted for several days after the SSW peak.

It is observed from Figure 3B 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 show the daytime TEC maximum around 45-50 TECu while the daytime maximum during the SSW event is around 30-35 TECu indicating a significant decrease of about 35%.

The TEC values during the following three 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. It is observed that 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, from 16:00 UT to 24:00 UT (13:00 to 21:00 LT) the VTEC values during these three days (DOY 25-27) are lower than those of the quiet-day (about 10 TEC units).

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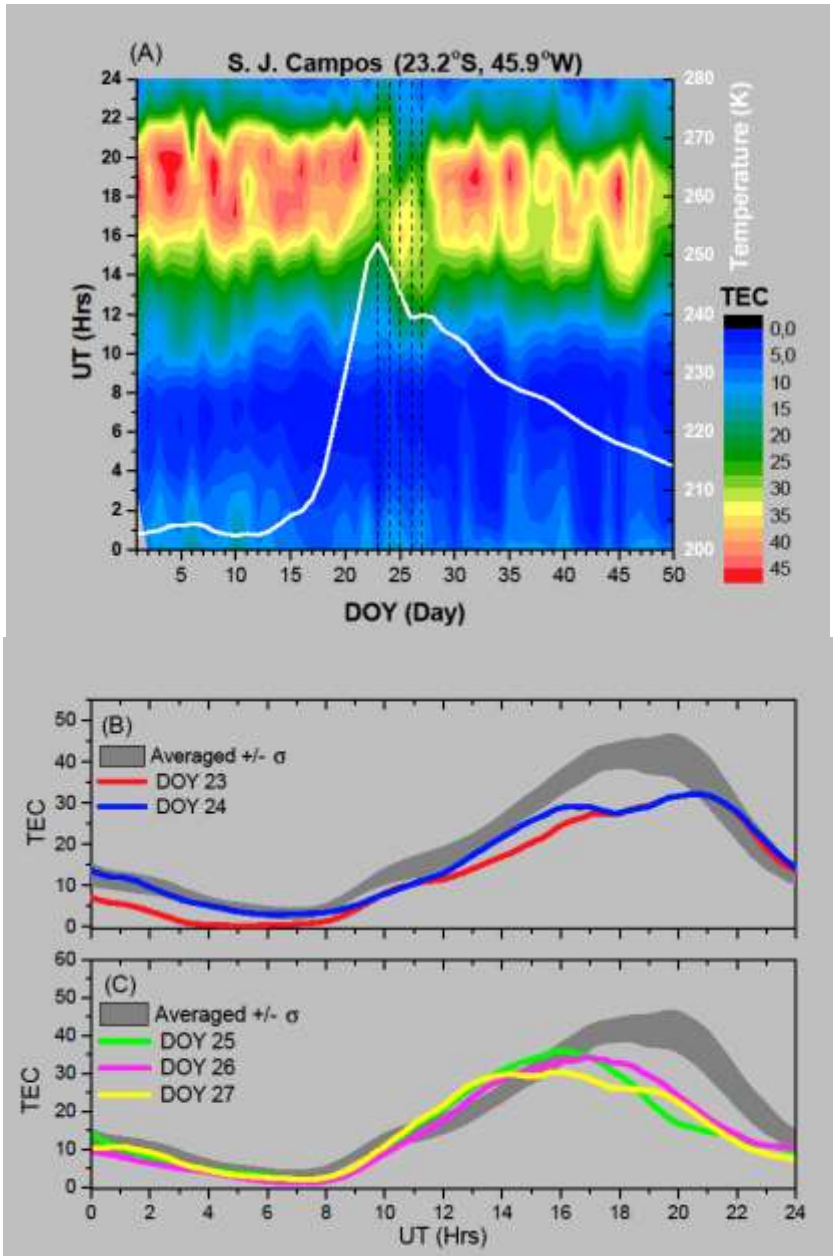


212

213 Figure 3. (A) Contour plot showing the VTEC variations with UT as a function of
214 DOY (January-February, 2009) at Sao Jose dos Campos (23oS, near the
215 EIA crest). The white solid line shows the average stratospheric
216 temperature variations between 60^0N to 90^0N at 10hPa (~30km), and the
217 dashed lines indicate the DOY from 23 to 27. (B). The VTEC diurnal
218 variations during disturbed days (DOY 23 and 24). The averaged quiet-

219 day VTEC is shown as gray bands with the band widths indicating ±1
220 standard deviation. (C) The same as (B) but for DOY 25, 26, and 27.
221
222 During 2009 the solar activity was very low and the VTEC from 24 UT to
223 11:00 UT in the morning was very low (VTEC < 15); considerable variations in
224 VTEC are not observed during this time. However, after 12 UT when the VTEC
225 increases significant changes are observed due to the effect of the SSW. Hence, in
226 order to highlight the VTEC changes during the 2009 SSW event, the VTEC
227 variations with UT as a function of DOY from 09:00 UT to 24:00 UT at 16 different
228 locations are presented in Figures 4A and 4B.
229
230 The contours presented in Figure 4 clearly indicate the SSW disturbance
231 effect in VTEC beginning in all 16 stations on DOY 23, just when the SSW reached
232 its maximum temperature and continuing for the next five-six days. Each station
233 has its particular response to the SSW disturbances, with different strength and
234 time of duration. However, it is very clear that the VTEC was perturbed during 5 or
235 6 days in all 16 stations indicating that the SSW event in the northern hemisphere
236 significantly influenced the electron density variations over the equatorial and low
237 latitudes in the southern hemisphere.
238
239 Significant portion of differences between different stations is most likely
240 related to the location of the station with regards to the location of the equatorial
241 ionization anomaly. Earlier studies have demonstrated that largest variations in
242 VTEC during SSW are observed at the crests of the EIA (Goncharenko et al.,

2010a, Liu et al., 2011), and 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 probably related with a local perturbation caused by MSTIDs and/or PWs disturbances. Since the geographical extent covered by the 16 stations is very large, 32.9o in latitude and 25.3o in longitude, it can be expected that the VTEC in each station is subject to different MSTIDs local sources disturbance or closed stations are subject to similar PW disturbances, but with different phases. The disturbance effects (SSW, MSTIDs, and PWs) are probably 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.

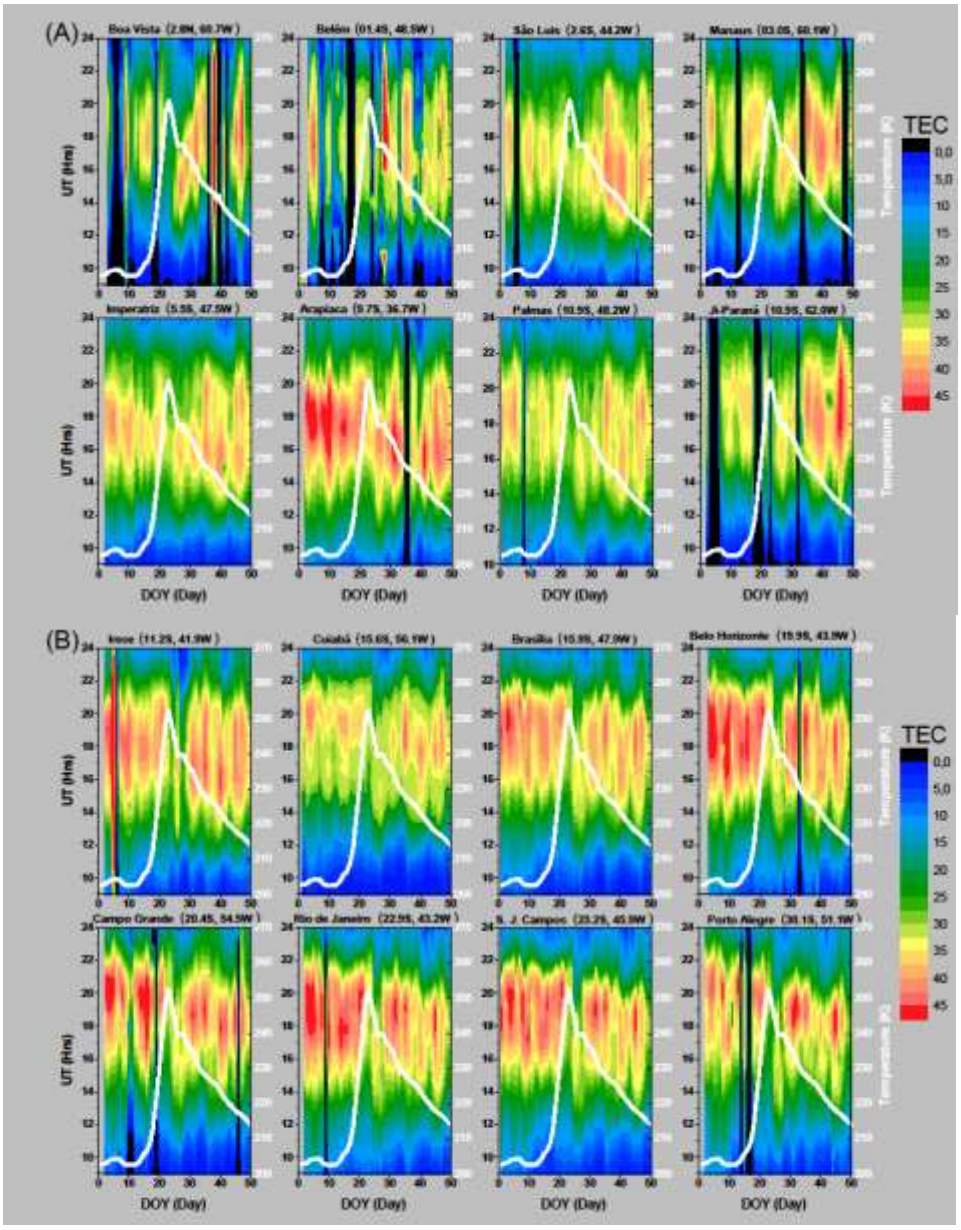


Figure 4. (A) VTEC variations with UT as a function of day of the year (January-February, 2009) for 8 stations over Brazilian sector, spanning from latitude 2.8^{o}N to 10.9^{o}S and longitude from 36.7^{o}W to 62.0^{o}W. (B) VTEC variation with UT as a function of day of the year (January-February, 2009) for 8 stations over Brazilian sector, spanning from latitude 11.2^{o}S to 30.1^{o}S and longitude 41.9^{o}W to 56.1^{o}W. The white solid lines show the

stratospheric temperature averaged between 60^{o}N to 90^{o}N at 10hPa (~30km).

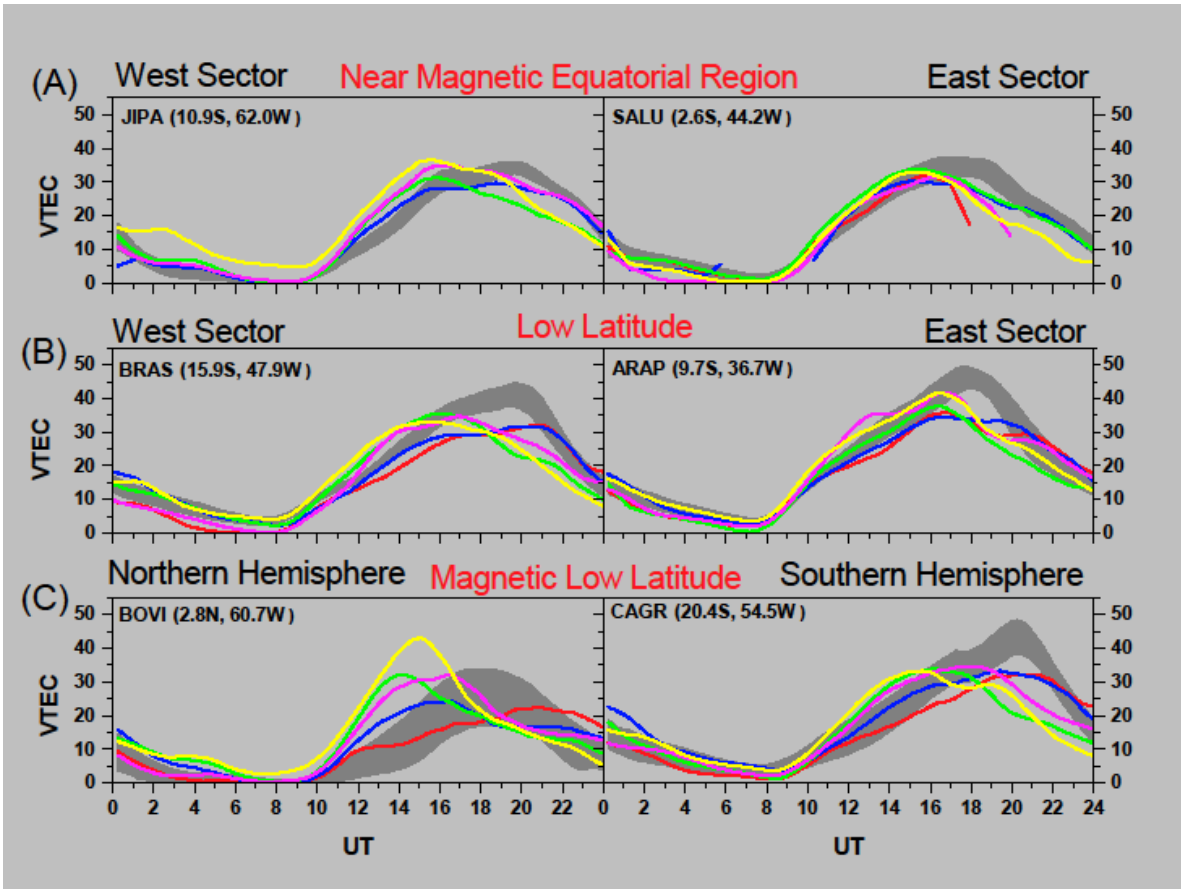


Figure 5. (A) The averaged quiet-day diurnal VTEC variations is shown as gray bands with the band widths indicating ±1 standard deviation and the variation of VTEC during the disturbed period (DOY 23 to 27) over near magnetic equatorial region (Ji-Parana - JIPA and Sao Luis - SALU). (B) The same as (A)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

magnetic North Hemisphere and Campo Grande (CAGR) located in the South Hemisphere.

Figure 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 grey bands for comparison. It is important to mention here that the two near equatorial stations (JIPA and SALU) are separated by 18^0 in longitude and the two low latitude stations (BRAS and ARAP) are separated by 11^0 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 quiet day averaged TEC show the daytime maximum of about 50 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

296 observed during the disturbed days is broad varying between 35 to 40 TECu and it
297 is much less compared to those of the quiet day which varies between 45 to 50
298 TECu around 17:00 UT.
299
300 Figure 5C shows the diurnal variations of VTEC at two magnetic low-latitude
301 stations (BOVI and CACR) one in northern and another one in the southern
302 hemisphere, which are separated by about 23^{o} latitude. These stations are shown
303 in Figure 1 with green icon. From the observations over these two stations it can be
304 observed that the VTEC in northern hemisphere was more affected by the SSW
305 than the VTEC in southern hemisphere. These hemispheric differences can be
306 attributed to the reason that the SSW occurred in the high latitude northern
307 hemisphere. The strong latitudinal dependence and hemispheric asymmetry of the
308 TEC disturbances observed in the present study during SSW are in agreement
309 with those reported earlier by Liu et al. (2011). However, the present study reveals
310 the important characteristics such as, latitudinal and hemispheric differences due
311 to SSW events with quantitative database in the South American sector.
312
313 A perusal of Figures 3A and 3B indicates that the electron density at the
314 anomaly crest locations in the South America sector was perturbed by the SSW
315 event. In addition, recently Goncharenko et al. (2010a) reported that, after the peak
316 in stratospheric temperature an enhancement of the EIA in the morning sector and
317 a suppression of the EIA in the afternoon sector are observed. Hence, in order to
318 investigate the day-to-day variability in the formation of EIA before and during the
319 SSW event the TEC data from a set of seven GPS receivers from equator to the

anomaly crest location and beyond are considered. The stations used in this investigation are shown along the black coloured 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 in Figure 6. In general, it is seen from this Figure that the EIA shows significant variability from one day to the other.

The high variability of the EIA is expected, but the formation of the EIA is usually observed around 20^0-25^0 S. 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-region. 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. Since the EIA were suppressed during 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.

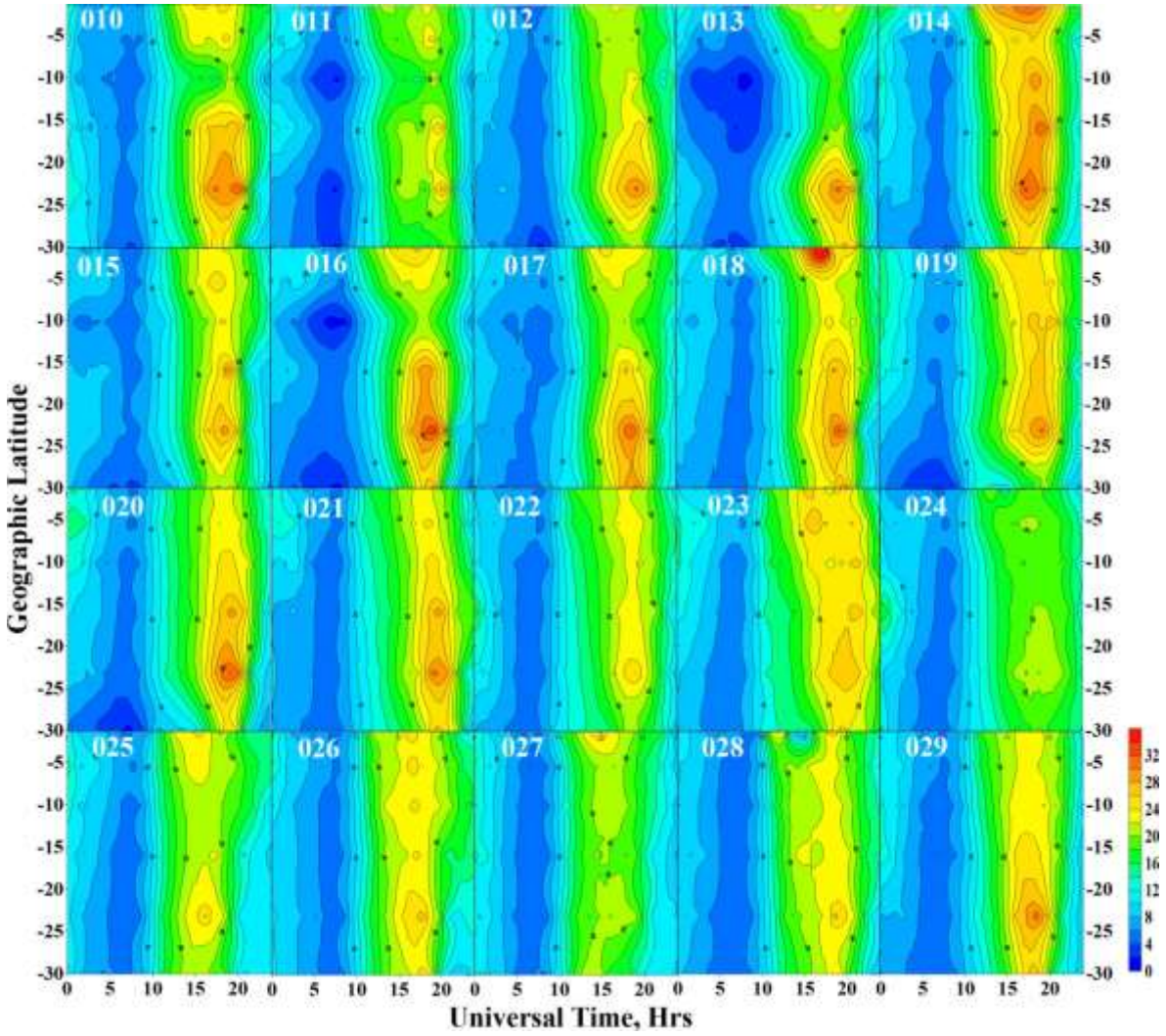


Figure 6. Contour plots showing the daily VTEC variation as a function of geographic latitude and UT from DOY 10 to DOY 29. The latitude starts from equator to the EIA crest in the southern hemisphere and beyond.

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 and SJCA. The diurnal variations of quiet day averaged values of h´F (ionospheric F region base height) and foF2 are shown as

gray bands. A perusal of Figure 7 (left panels) indicates 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 50-75km 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 alternating increase and decrease of h´F in the evening hours over the Indian sector during the SSW of January 2008 period. In addition, they pointed out that the strengthening of the Pre-Reversal Enhancement (PRE) 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 during 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 lead 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 – 04:00 UT) and reaches 2-6 MHz, while increase of varying magnitude is observed mostly in the morning sector. 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. However, earlier studies of the same events have reported that ionospheric perturbations caused by SSW are stronger in the American sector than in the Asian sector for January 2009 SSW event (Goncharenko et al., 2010b, Liu et al., 2011), and stronger than in the Asian and African sector for January 2013 SSW event (Goncharenko et al., 2013). Our observations provide additional evidence of significant longitudinal variations in ionospheric response to SSW.

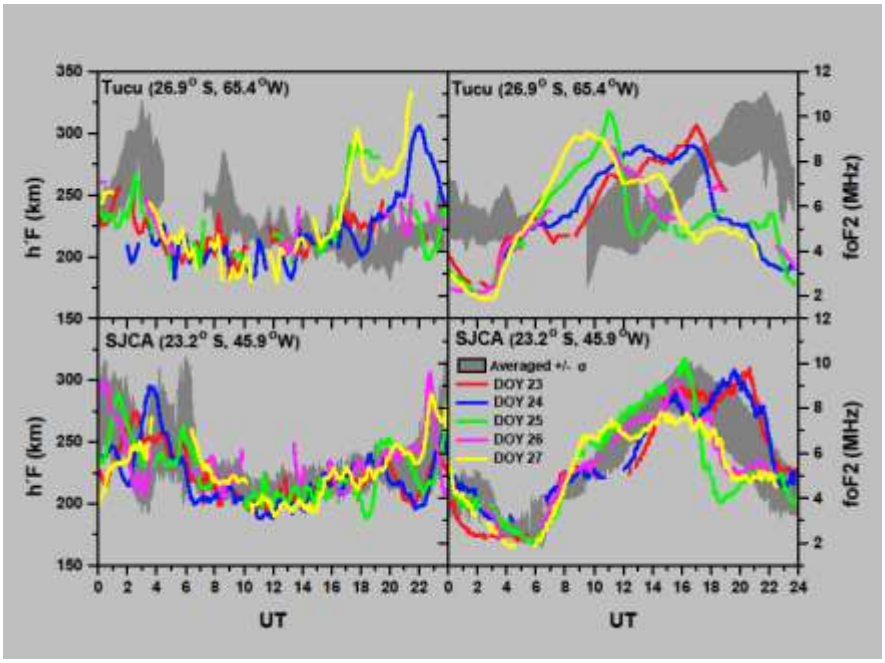


Figure 7. Variations of h´F and FoF2 during the period from DOY 23 to DOY 27 at Tucuman (TUCU) and Sao Jose dos Campos (SJCA). The averaged quiet-day h´F and foF2 values are shown as gray bands with the band widths indicating ±1 standard deviation.

388

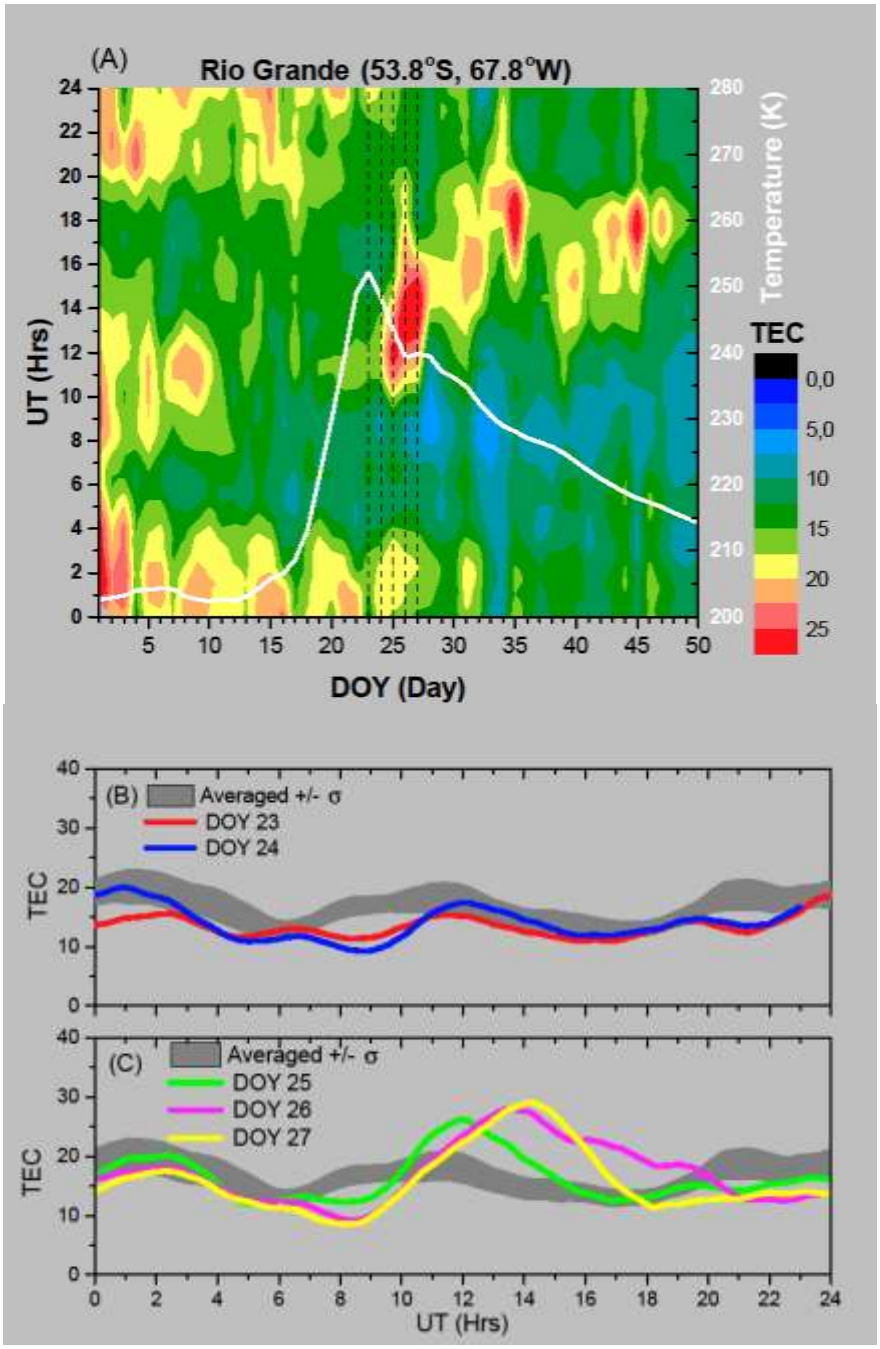
389 **3.3 VTEC at Mid-Latitude**

390 From the above results, it can be observed that the equatorial and low-
391 latitude ionosphere in the southern hemisphere is significantly disturbed by the
392 2009 SSW event in the northern hemisphere. Since the disturbances reach up to
393 the equatorial and low-latitudes, some ionospheric coupling between low- and mid-
394 latitudes should be expected. Therefore, the VTEC variations over Rio Grande
395 (53.8^{o}S) have been studied to understand the mid-latitude ionospheric response
396 for the SSW event. The contour plot presented in Figure 8A shows the day-to-day
397 variations of VTEC as a function of DOY and UT, during January-February 2009
398 (summer season) in the southern hemisphere. It is readily observed form this
399 Figure that the VTEC is strongly disturbed during day-time (10:00 to 16:00 UT) for
400 several days (DOY 24 to DOY 28). During this time, VTEC over Rio Grande
401 increases almost by a factor of 2 (from 10-15 TECu to ~25TECu). In addition, the
402 disturbance lasts for several days after DOY 28 (DOY 29-36), although it becomes
403 weaker and shifts to later local times.

404

405 The quiet day averaged diurnal variations of TEC are presented in Figure 8 B and
406 C as gray bands and the thickness of these bands represent the ± standard
407 deviation of VTEC. We note that quiet-time VTEC at this time does not present
408 strong day-to-night variations. The colored lines are the diurnal variation of the
409 TEC during disturbed days (DOY 23 and 24 are in Figure 8B and DOY 25-27 are in
410 Figure 8C). Comparing the VTEC variations during disturbed days with those of the
411 averaged quiet-day diurnal variation reveals that, on the DOY 23 and 24, the

412 disturbances are moderate. The VTEC variations during DOY 25 to 27 show large
413 deviations compared to the quiet day averaged variations, with daytime (13-16 UT)
414 increase up to a factor of 2 (10-15 TECu), and nighttime-to-morning (7-9UT)
415 decrease by 5-7 TECu. These strong variations observed in the VTEC over Rio
416 Grande are surprising since the SSW is in the northern hemisphere. For the strong
417 variations to occur in the Southern Hemisphere, the SSW's influence must have
418 propagated up to the mid-latitudes in the opposite (southern) hemisphere. This
419 highlights the importance of studying the changes in the ionosphere due to SSW in
420 a broad range of latitudes, since a single stratospheric event at high latitudes in the
421 Northern Hemisphere is disturbing the whole ionosphere, suggesting that the SSW
422 produces ionospheric perturbations from Pole to Pole.



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424

425 Figure 8. (A) VTEC variations with UT as a function of DOY (January-February,
426 2009) at Rio Grande (53.8°S, mid-latitude), the white solid line show the
427 average stratospheric temperature variation between 60°N to 90°N at
428 10hPa (~30km), and the dashed lines indicate the DOY from 23 to 27.
429 (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 (B) but for DOY 25, 26, and 27.

4. Conclusions

In the present investigation, VTEC measurements from dual frequency GPS receivers over 17 GPS locations covering a large geographical area from 2.8^{o}N to 53.8^{o}S latitudes and 36.7^{o}W to 67.8^{o}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 main objective of the present study is to simultaneously investigate the ionospheric response at equatorial, low and mid-latitudes as well as the variability in the EIA characteristics. The results observed in the present investigation are summarized below.

a) After the occurrence of the peak in the stratospheric temperature in the present 2009 SSW event, a large disturbance has been observed at all of the 16 different locations from equator to the low latitudes in the Southern Hemisphere. These disturbances are found to be retained for a long duration of about five to six days.

b) 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.

c) 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 50-70km 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.

d) The VTEC variations in the southern mid-latitudes (53.8^{o}S, Magnetic 43.6^{o} S) have also shown significant disturbances during the present Northern SSW event. This highlights the importance of the investigations on ionospheric response to the stratospheric warming since the SSW event in one hemisphere can create strong perturbations in the ionosphere from one pole to the other.

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583 **Table Captions**

584 **Table 1-** Details of the GPS and digital ionosonde symbols, latitudes and

585 longitudes sites used in the present investigation.

586

Site	Lat. Geog. +N	Lon. Geog. W	Lat. Mag. +N	Lon. Mag E
GPS stations				
Boa Vista - BOVI	2.8	60.7	12.6	11.7
Belem - BELE	-1.4	48.5	7.8	23.9
São Luis - SALU	-2.6	44.2	6.3	28.1
Manaus - MANA	-3.0	60.1	12.8	12.3
Imperatriz - INPE	-5.5	47.5	3.7	24.6
Arapiaca - ARAP	-9.7	36.7	-1.4	34.9
Palmas - PALM	-10.2	48.2	-1.4	23.5
Ji-Paraná - JIPA	-10.9	62.0	-0.9	10.0
Irece - IREC	-11.2	41.9	-2.4	29.6
Cuiabá - CUIB	-15.6	56.1	-5.8	15.5
Brasília - BRAS	-15.9	47.9	-6.6	23.4
Belo Horizonte - BEHO	-19.9	43.9	-10.9	27.0
Campo Grande - CACR	-20.4	54.5	-10.7	16.8
Rio de Janeiro - RIOJ	-22.9	43.2	-13.9	27.4
S. J. Campos - SJCA	-23.2	45.9	-14.0	24.8
Porto Alegre - POAL	-30.1	51.1	-20.5	19.4

Rio Grande - RIOG	-53.8	67.8	-43.6	3.6
Ionosonde stations				
S. J. Campos - SJCA	-23.2	45.9	-14.6	24.7
Tucumán - TUCU	-26.9	65.4	-16.8	6.2

587

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Figures Captions

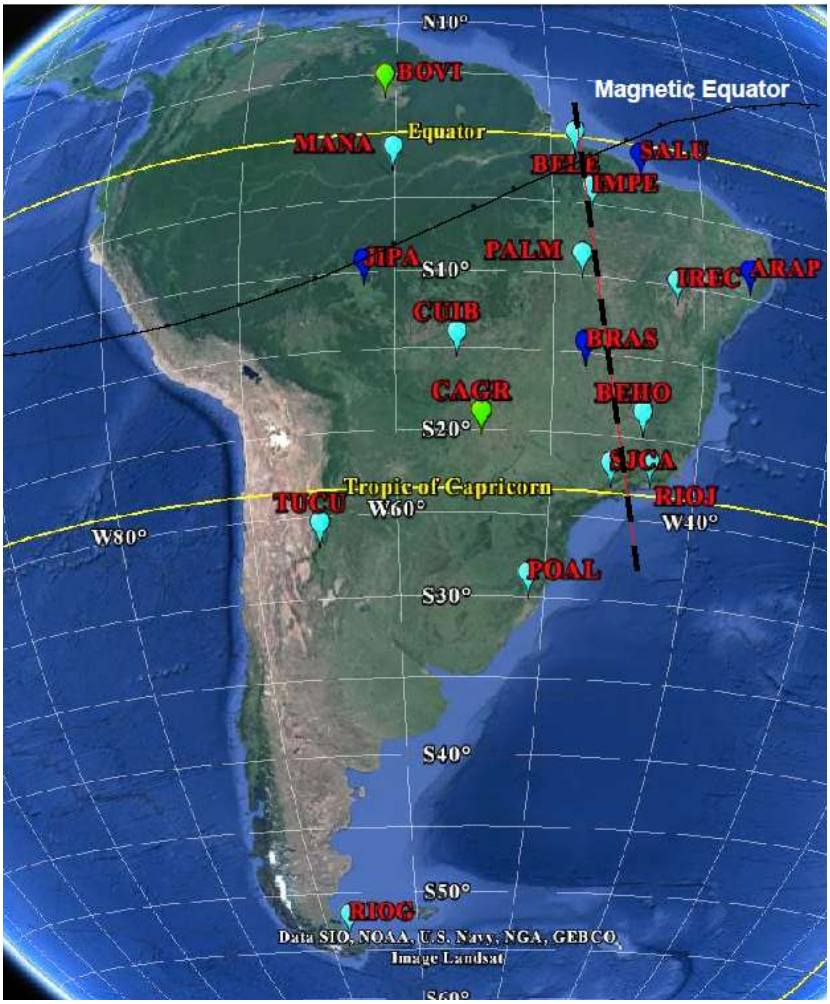
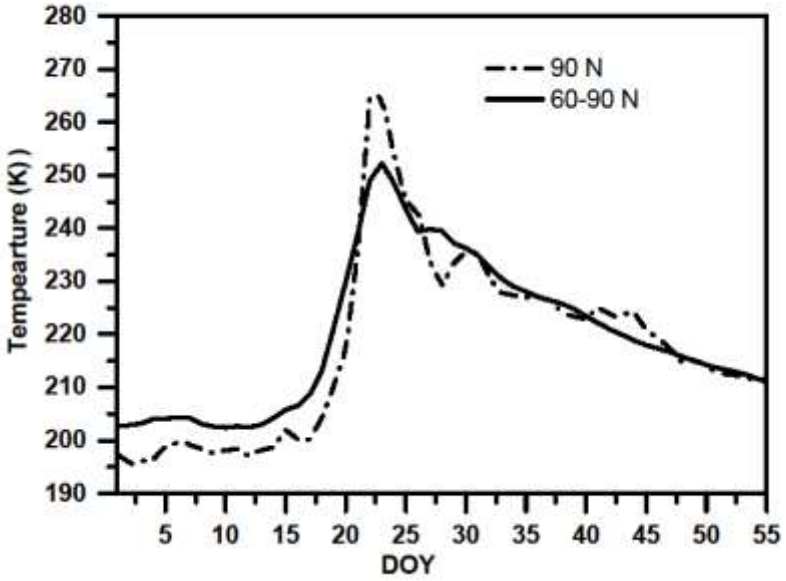


Figure 1- South American map showing the locations of GPS and Digital Ionosonde stations. The blue and green icons indicate stations that are analyzed in more details. The GPS stations along the black colored dashed line are used to study the EIA characteristics during the present SSW event.



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596 Figure 2- Plots showing the stratospheric temperatures at 90oN and 60o-90oN
597 (averaged) at 10 hPa (~30 km) in the northern hemisphere during the period
598 January-February, 2009.

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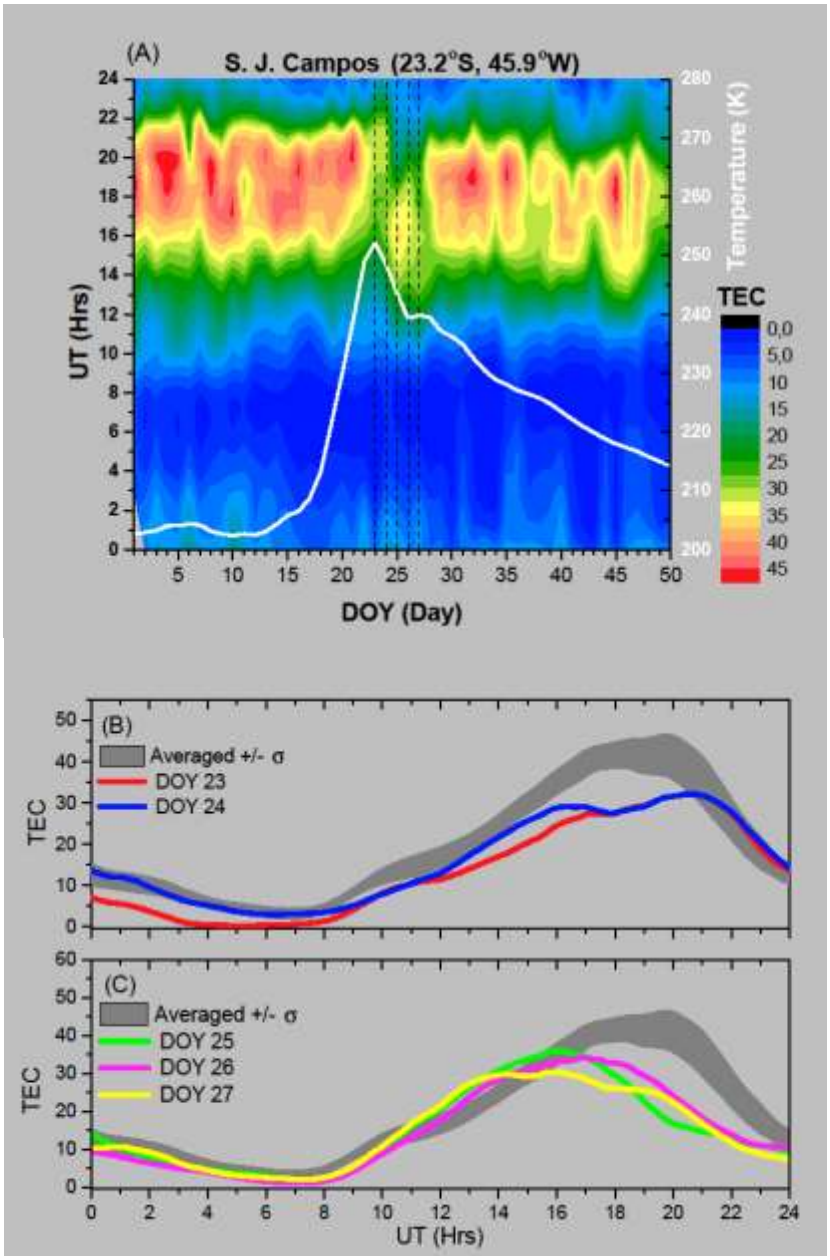

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602 Figure 3- (A) Contour plot showing the VTEC variations with UT as a function of
603 DOY (January-February, 2009) at Sao Jose dos Campos (23oS, near the EIA
604 crest). The white solid line shows the average stratospheric temperature
605 variations between 60oN to 90oN at 10hPa (~30km), and the dashed lines
606 indicate the DOY from 23 to 27. (B). The VTEC diurnal variations during
607 disturbed days (DOY 23 and 24). The averaged quiet-day VTEC is shown as

608 gray bands with the band widths indicating ±1 standard deviation. (C) The
609 same as (B) but for DOY 25, 26, and 27.

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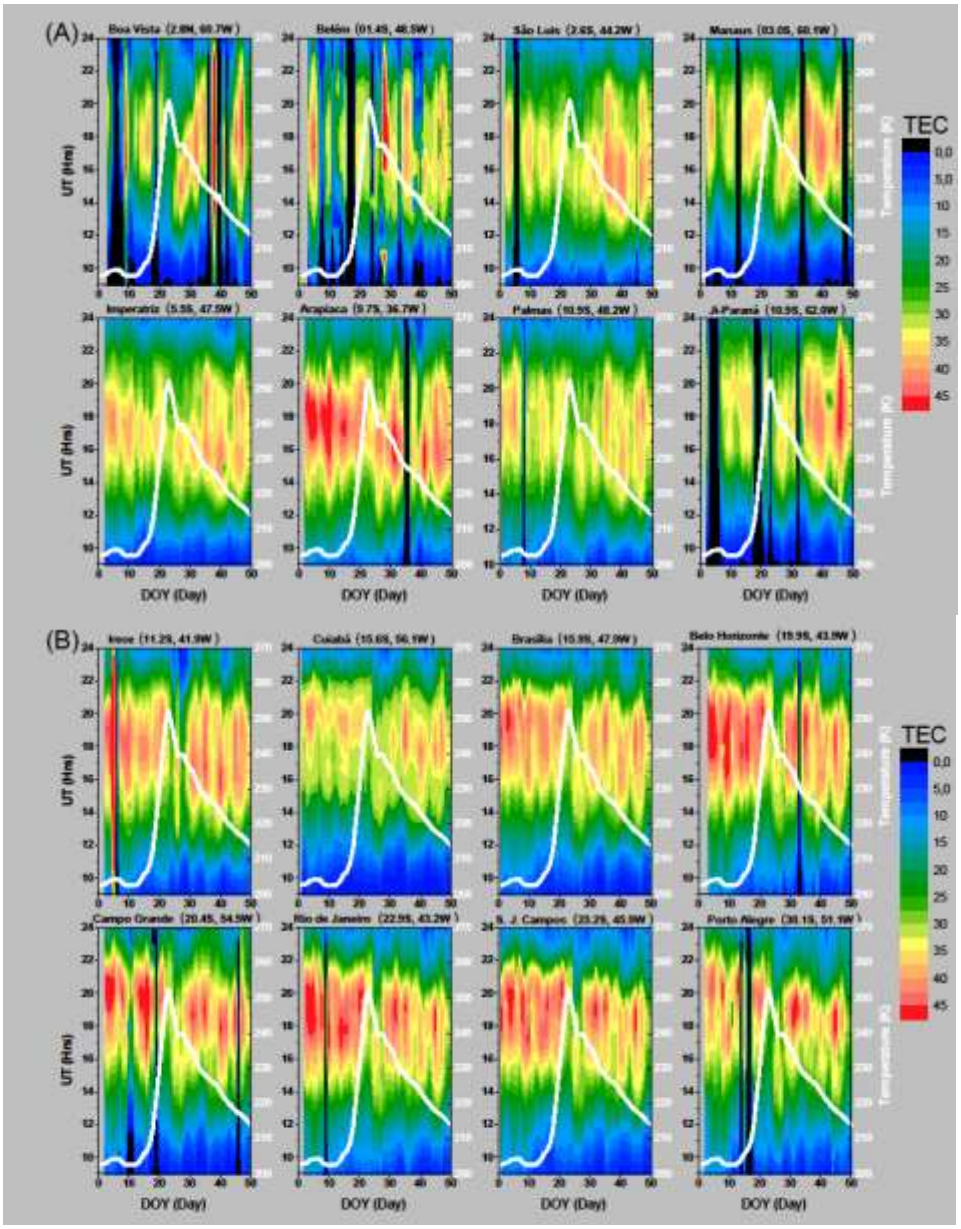
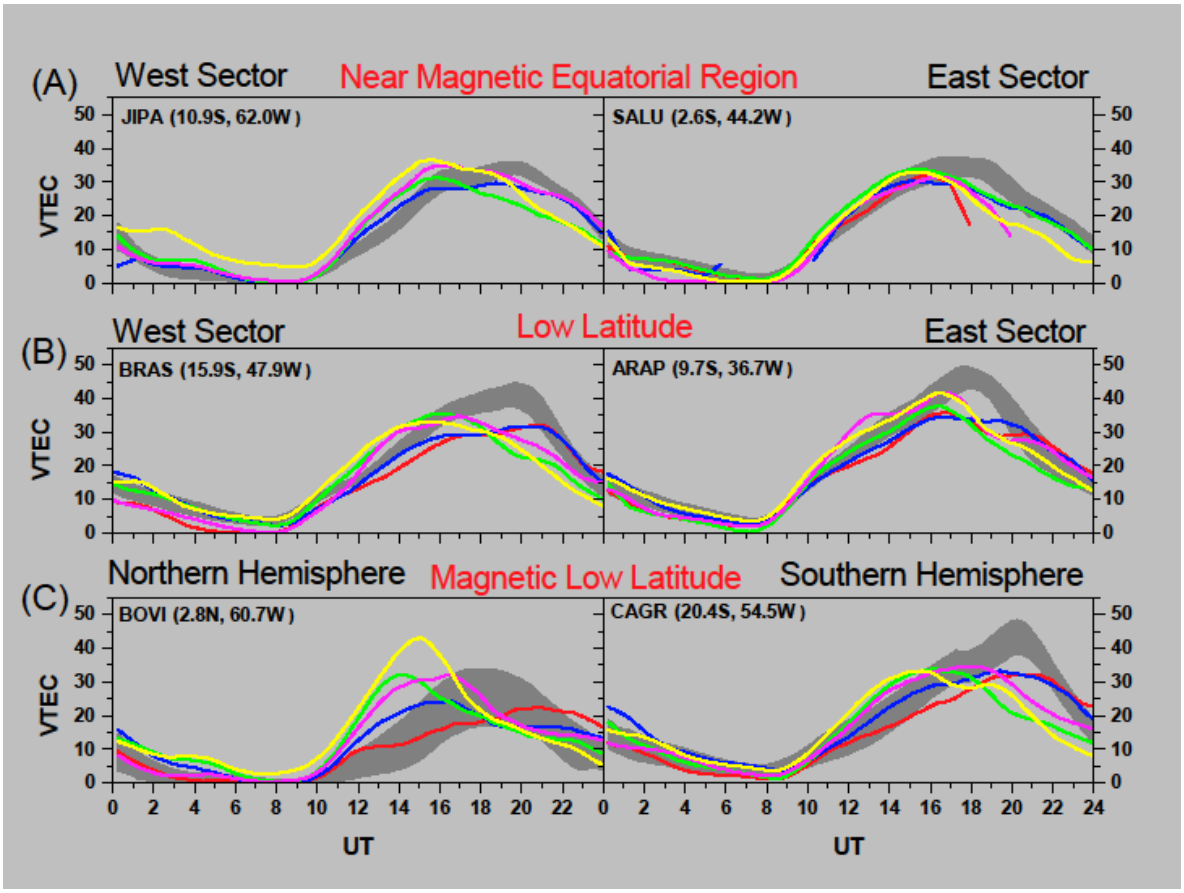


612

613 Figure 4- (A) VTEC variations with UT as a function of day of the year (January-
614 February, 2009) for 8 stations over Brazilian sector, spanning from latitude
615 2.8oN to 10.9oS and longitude from 36.7oW to 62.0oW. (B) VTEC variation

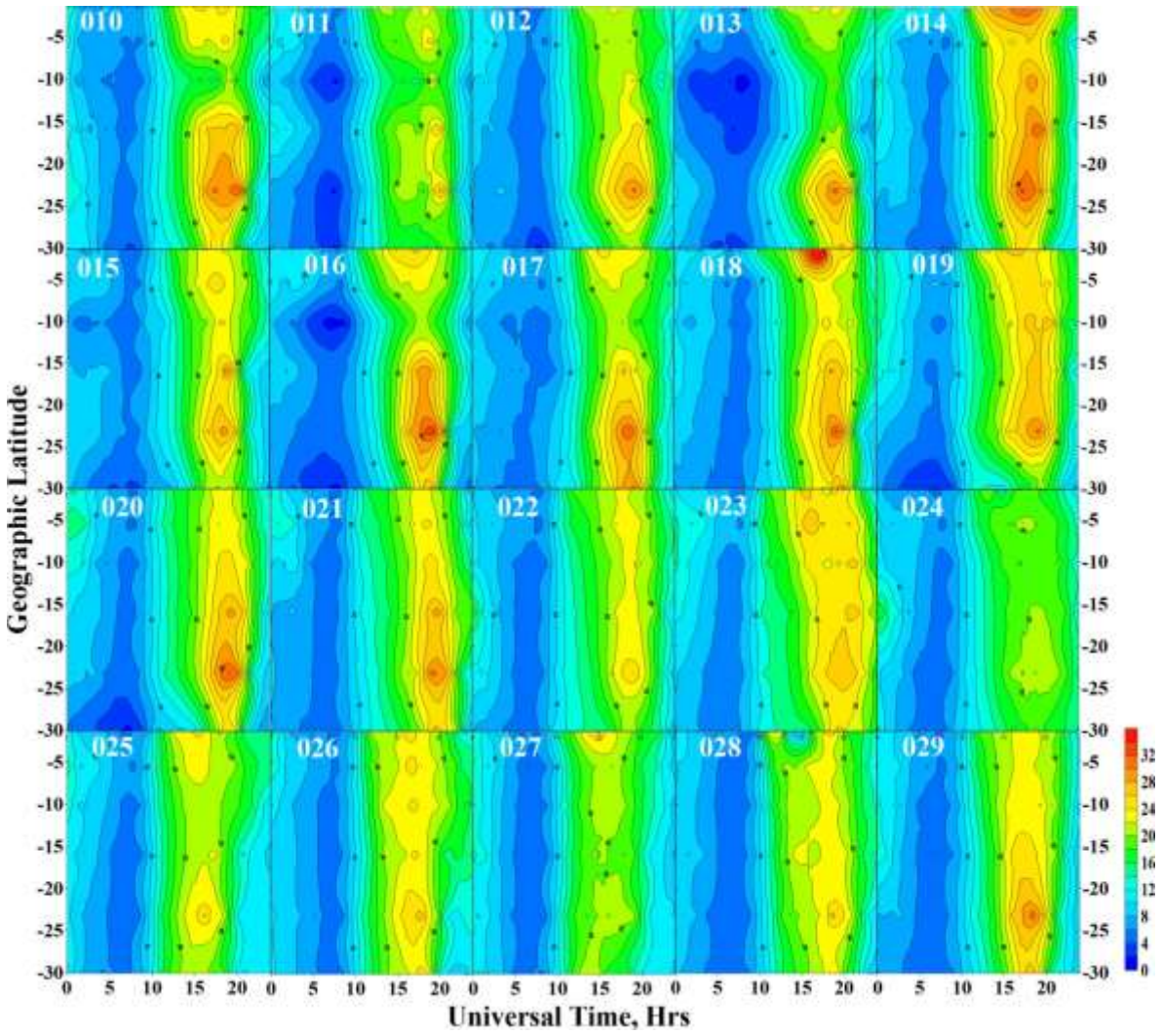
616 with UT as a function of day of the year (January-February, 2009) for 8 stations
617 over Brazilian sector, spanning from latitude 11.2oS to 30.1oS and longitude
618 41.9oW to 56.1oW. The white solid lines show the average stratospheric
619 temperature variation between 60oN to 90oN at 10hPa (~30km).



620

621 Figure 5- (A) The averaged quiet-day diurnal VTEC variations is shown as gray
622 bands with the band widths indicating ±1 standard deviation and the variation
623 of VTEC during the disturbed period (DOY 23 to 27) over near magnetic
624 equatorial region (Ji-Parana - JIPA and Sao Luis - SALU). (B) The same as (A)
625 but for low-latitude (Brasilia - BRAS and Arapiaca - ARAP). (C) The same as

626 (A) but for Boa Vista (BOVI) located in the magnetic North Hemisphere and
627 Campo Grande (CAGR) located in the South Hemisphere.



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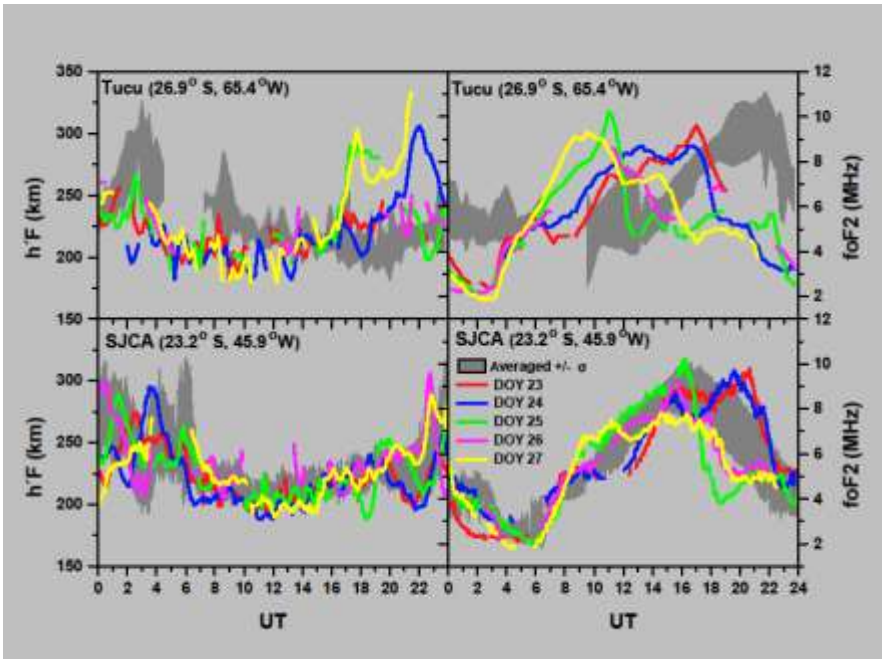
629 Figure 6- Contour plots showing the daily VTEC variation as a function of
630 geographic latitude and UT from DOY 10 to DOY 29. The latitude starts from
631 equator to the EIA crest in the southern hemisphere and beyond.



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633 Figure 7- Variations of h´F and FoF2 during the period from DOY 23 to DOY 27 at
634 Tucuman (TUCU) and Sao Jose dos Campos (SJCA). The averaged quiet-day
635 h´F and foF2 values are shown as gray bands with the band widths indicating
636 ±1 standard deviation.

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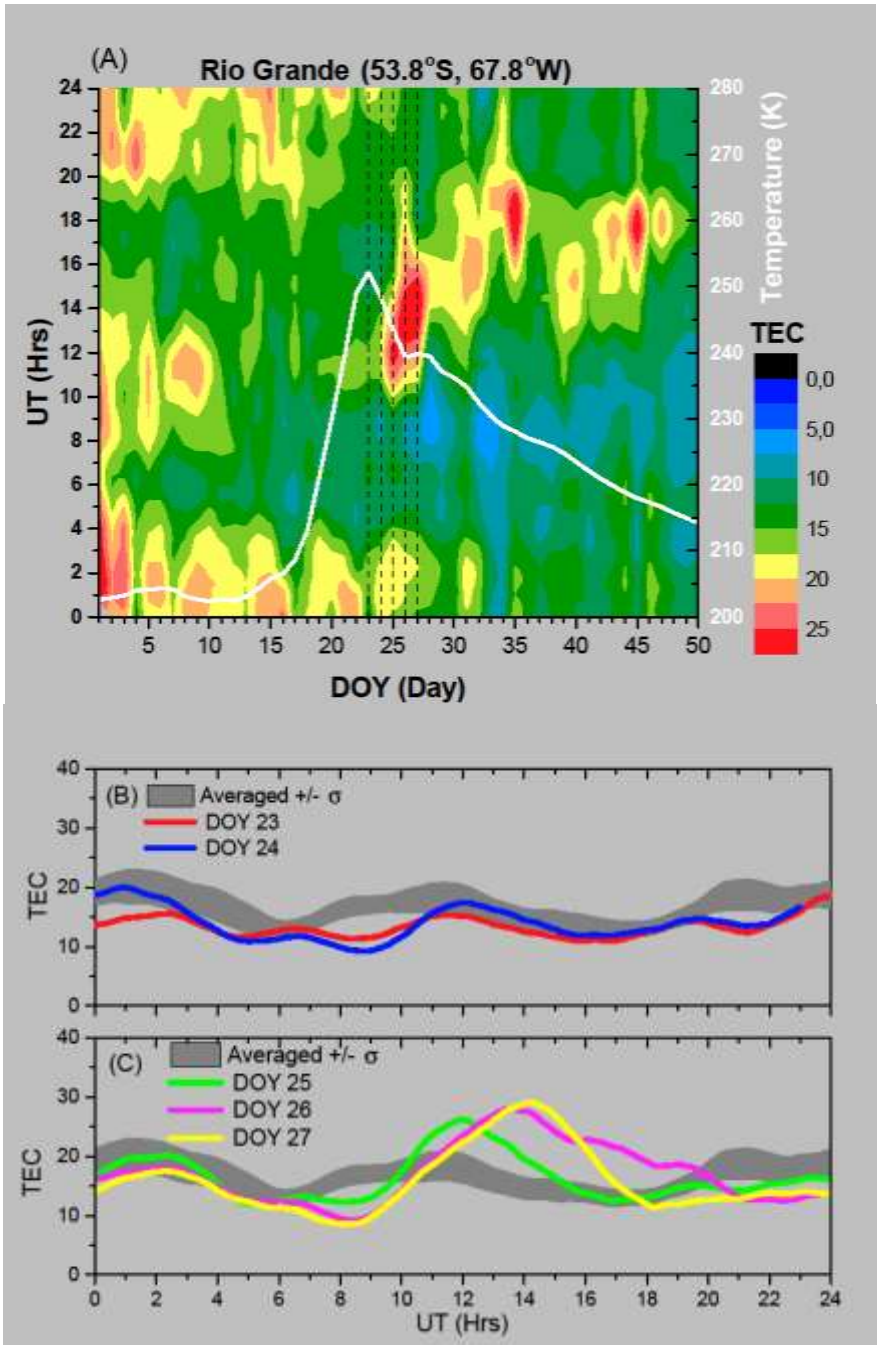

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640 Figure 8- (A) VTEC variations with UT as a function of DOY (January-February,
641 2009) at Rio Grande (53.8oS, mid-latitude), the white solid line show the
642 average stratospheric temperature variation between 60oN to 90oN at 10hPa
643 (~30km), and the dashed lines indicate the DOY from 23 to 27. (B) The
644 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 (B) but for DOY 25, 26, and 27.