INVESTIGATING SOUTHERN HEMISPHERE MID-LATITUDE NIGHTTIME TEC ENHANCEMENTS DURING A LOW SUNSPOT NUMBER PERIOD WITH GPS AND TOPEX

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ABSTRACT

The state of the ionization of the upper atmosphere at low and mid latitudes in the Australian region has been studied by investigating total electron content (TEC) obtained by the dual-frequency group path and phase path Global Positioning System technique. For the low sunspot number time period of March 1995-February 1996, one week of data centered on the regular world days for each month have been used to investigate nighttime mid-latitude peaks occurring around midnight in the Australian region. TEC from TOPEX provided additional information related to the formation of the nighttime peaks. Although nighttime TEC enhancements have been observed previously, the origin of these large increases does not have general agreement among researchers. From the results of the present study it appears that the development of midnight TEC enhancements is a direct consequence of the low latitude processes occurring at around the time of ExB drift velocity reversal. Accordingly the midnight TEC enhancement appears to be a reverse-fountain-related formation at mid latitude and the primary source of plasma is the reverse fountain. The monthly GPS plots show a seasonal variation of nighttime TEC enhancement. TOPEX data plots provided the spatial variability of large-scale ionospheric features under different geomagnetic conditions during the season of autumnal equinox.

INTRODUCTION

Since Arendt and Soicher (1964) revealed that the nocturnal ionospheric electron content can be anomalously high, the phenomena of nighttime TEC enhancements have been reported and further established by many researchers. However the physical processes underlying their formation are still not properly understood and the number of investigations on the Southern Hemisphere phenomenon is much less.

The aim of this project was to study southern mid-latitude nighttime TEC enhancements occurring around midnight at low sunspot numbers by analyzing satellite data and to interpret them in terms of the relevant theories. The terrestrial TEC data, obtained from the Navstar GPS tracking stations in the Australian region, was supplemented by TOPEX over the ocean TEC measurements. The longitude chain of AUSLIG and NASA/JPL ground-based receiver stations are located, from North to South, at Guam (13.59°;144.85°E), Townsville (-19.20°;146.46°E), Tidbinbilla (-35.38°;148.97°E) and Hobart (-42.80°;147.43°E). The GPS database for this study was established by regular downloading of RINEX observational and TEC files through the Internet. These were reduced to GPS TEC data by custom made computer programs. During this procedure corrections for cycle slips, potential drop-outs, and satellite and receiver biases supplied by JPL were made. Data from long and continuous TOPEX passes mainly from the Pacific and Indian Oceans were selected. The TOPEX data are stored on CD-ROMs and each CD contains the recordings of two complete cycles. The satellite radar data were reduced to TEC values and averaged over 20 seconds in order to minimize the noise effect of waves.

The GPS technique uses the dual-frequency (L_1,L_2) group path ($\Delta P'$) and phase path data ($\Delta\phi$) in order to obtain absolute differential time delay ($\delta\Delta T$) and relative differential carrier phase advance ($\delta\Delta\phi$) values. These quantities are proportional to the integral of electron density and can be used to obtain slant GPS TEC values through the calculation of the baseline (Klobuchar, 1996):

$$\text{slant GPS TEC} = \int_R^S N\,ds = \frac{2cL_2}{K}\left(\frac{L_2^2}{L_1^2 - L_2^2}\right)\delta\,\Delta\phi + \text{baseline} \quad (1)$$

where $L_1 = 1.57542\,\text{GHz}$, $L_2 = 1.2276\,\text{GHz}$ $K = 80.62\,(m^3/s^2)$

The vertical value can be obtained if the angle of zenith (χ), measured at 400 km median ionospheric height, is known (see Equation 2). This is the sum of ionospheric and plasmaspheric contents, since the orbital height of the satellite (20,183 km) is in the range of the plasmasphere.

$$\text{vertical GPS TEC} = \text{slant GPS TEC} * \overline{\cos\chi} \quad (2)$$

The TOPEX technique uses the differential group path defect ($\delta\Delta P'$), known as ionospheric height correction, measured between the Ku- and C-band frequencies by the onboard altimeter at nadir. This allows one to obtain a vertical ionospheric TEC directly (Imel, 1994):

$$\text{TOPEX TEC} = \frac{\delta\Delta P' f_1^2}{-403} \quad (3) \quad \text{where: } \delta\Delta P' \text{ is in mm and } f_1 = 13.65\,(\text{GHz})$$

EXPERIMENTAL RESULTS AND DISCUSSION

Nighttime TEC enhancements have been detected by 1995 and 1996 GPS data during the seasons of autumnal equinox (March, April and May), winter (June, July and August), vernal equinox (September, October and November) and summer (December, January and February). For each season, a monthly average plot was obtained to show the diurnal and seasonal TEC variation. Figure 1 shows a representative plot for each season and these are April, July, October and December. The nighttime sectors of the April, July and October plots are characterized by the development of pre-midnight and post-midnight peaks at 22 LT and 3 LT, respectively. Apart from October, when the pre-midnight peak was more prominent, the peaks were equally well formed before and after midnight. In December a peak occurred at local midnight and the post-midnight peak was absent. On the plots of vertical TEC against geographic latitude, the nighttime peaks appeared as single or double peak formations. The major peak is usually situated at lower (around -33°) and the minor peak is at higher (around -39°) geographic latitudes regardless to the season. The theoretical TEC values, generated by running the 1.6 version of Parameterized Ionospheric Model (PIM), were compared directly to the experimental plots. As Figure 1 indicates the theoretical values are generally below the experimental ones and the model curve shows little or no resemblance at all to the experimental one.

The April pre-midnight GPS observations were confirmed by TOPEX results. In Figure 2(a) a TOPEX pass located offshore of the Australian East Coast illustrates an anomalous nighttime peak before midnight. The matching GPS latitudinal plot was constructed from data of 2 hours covering the local time range of TOPEX pass at mid latitudes (see Figure 2(b)). The direct comparison of plots of different techniques (see Figure 2(c)) detected the same phenomenon at 150 (°E) and –32 (°) geographic location around local midnight and confirmed the validity of the finding. The PIM generated TEC values showed a better agreement at low latitudes than at mid latitudes where they were generally lower.

The development of the pre-midnight TEC enhancement was studied by descending TOPEX passes situated entirely in the nighttime sector across the Pacific Ocean. As the equator crossing local time of these passes change by only a small amount from one crossing to the next, the development of the nighttime peak could be followed spatially on each successive satellite track. This investigation resulted in the recognition of various equatorial fountain-related ionospheric features at around the time of occurrence of the pre-midnight TEC enhancement. These are the

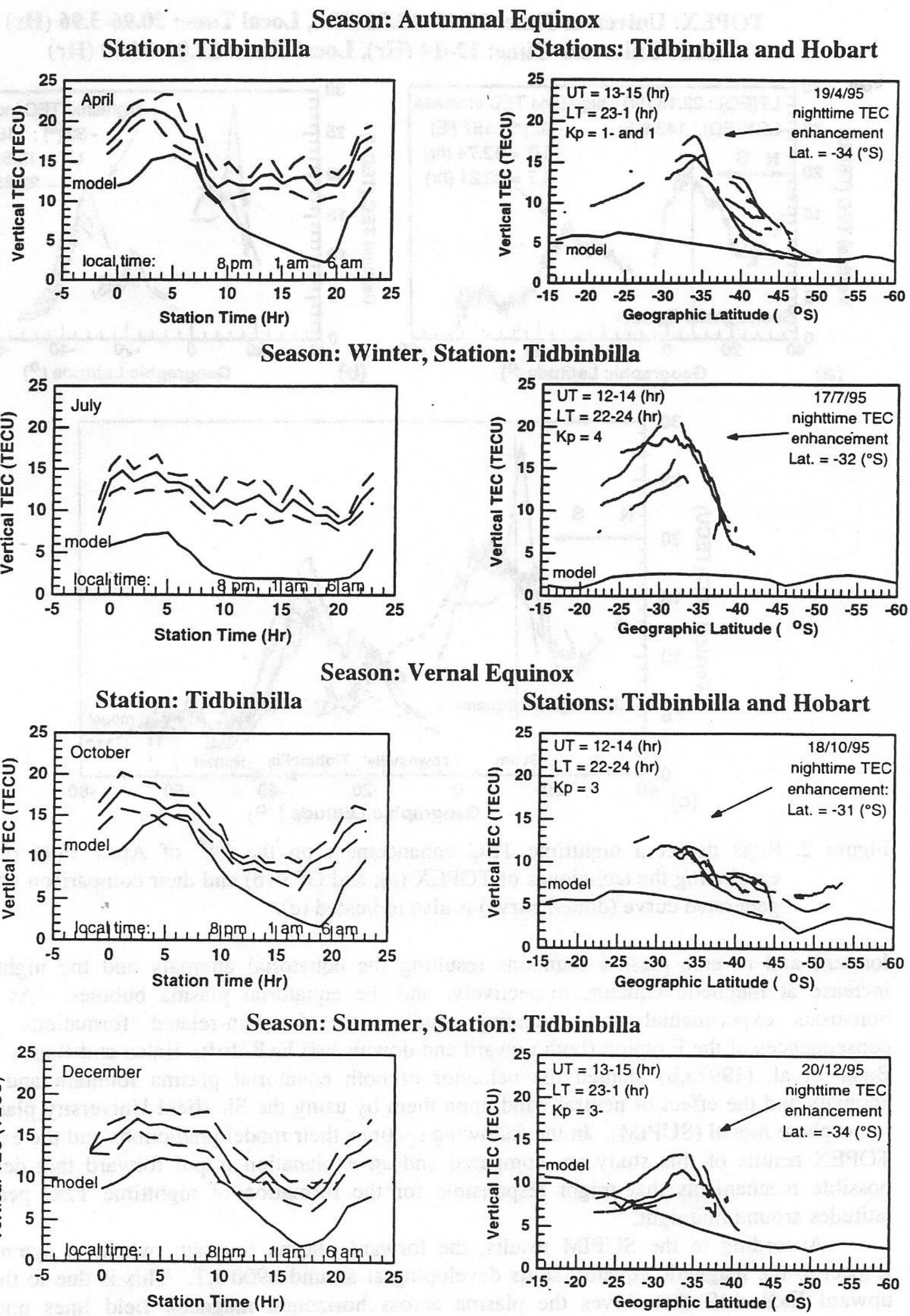

Figure 1. Mean monthly averaged TEC plots (left panels) and latitudinal maps (right panels) show nighttime TEC enhancements. PIM generated TEC curves are also shown for comparison.

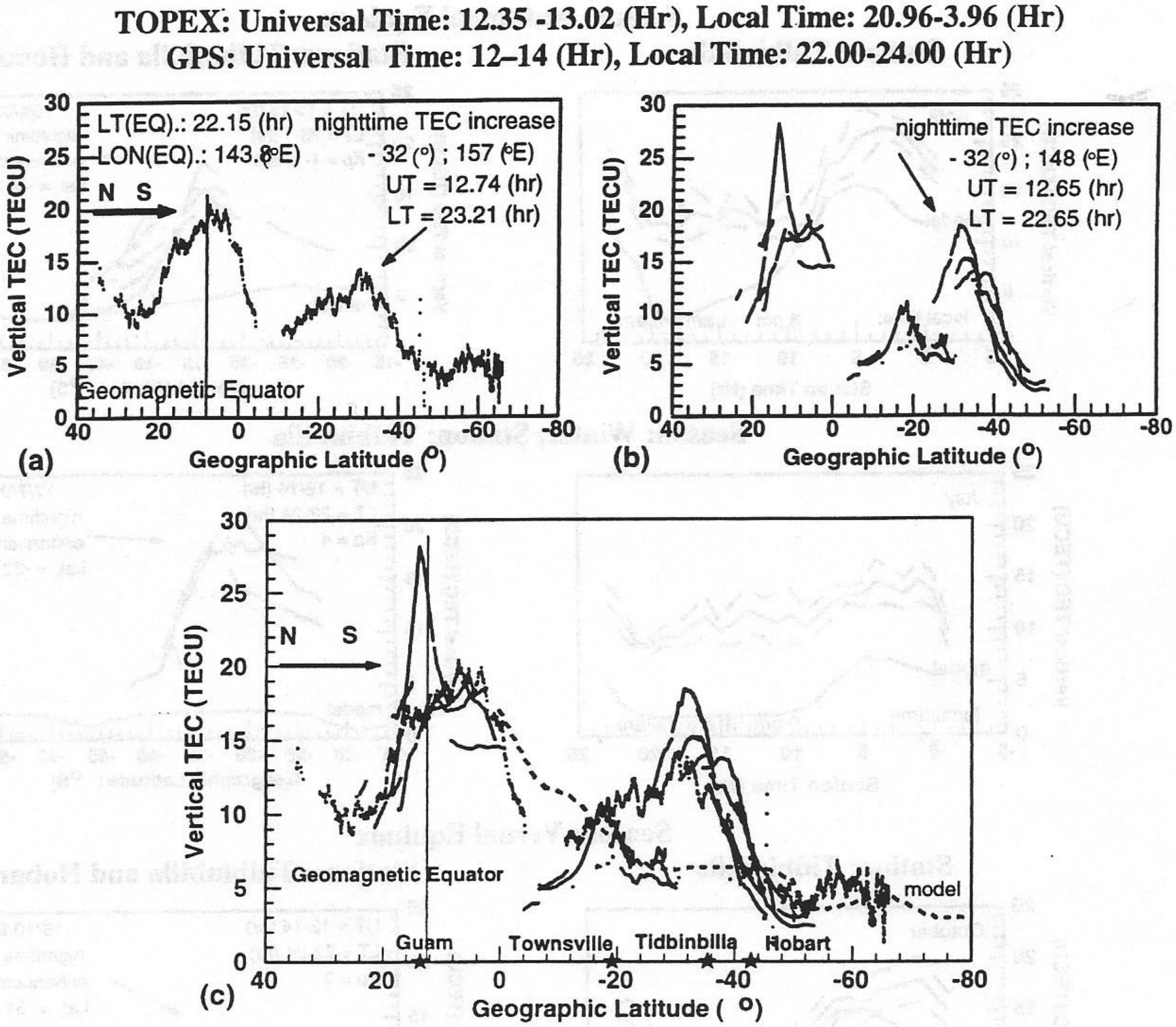

Figure 2. Plots depict a nighttime TEC enhancement on the 24th of April 1995 observed by employing the techniques of TOPEX (a), and GPS (b) and their comparison where a PIM generated curve (dotted curve) is also indicated (c).

forward and reverse plasma fountains resulting the equatorial anomaly and the nighttime TEC increase at magnetic equator, respectively, and the equatorial plasma bubbles. As shown by numerous experimental and modeling studies, the fountain-related formations are direct consequences of the F region (both upward and downward) **ExB** drift. Balan and Bailey (1995) and Balan et al. (1997a,b) studied the behavior of both equatorial plasma fountain and equatorial anomaly and the effect of neutral wind upon them by using the Sheffield University plasmasphere-ionosphere model (SUPIM). In the following sections their model predictions and the experimental TOPEX results of this study are compared and an explanation is put forward that describes the possible mechanisms that might responsible for the formation of nighttime TEC peaks at mid latitudes around midnight.

According to the SUPIM results, the forward plasma fountain, which is symmetric with respect to the magnetic equator, starts developing at around 0900 LT. This is due to the F region upward **ExB** drift that drives the plasma across horizontal magnetic field lines until it loses momentum and diffuses down the magnetic field lines and away from the magnetic equator due to the forces of gravity and pressure gradient. The end result is the equatorial anomaly characterized by a trough at the magnetic equator and two crests at about $\pm$ 17° magnetic latitudes (Appleton, 1946). Both the equatorial plasma fountain and anomaly are symmetric in the absence of neutral winds. The effects of neutral winds can cause north-south asymmetries that arise through the offset between the geomagnetic and geographic equators. In this study asymmetrical equatorial anomalies were recognized from TOPEX passes illustrated on Figures 3(b) and 3(c). After about 1700 LT the vertical upward **ExB** drift velocity is believed to undergo a prereversal strengthening that peaks at around 1800 LT. At this time the effect of neutral wind upon the plasma fountain is minimal due to the impulsive response of the ionosphere to the sudden strengthening of the F region drift. The plasma density largely becomes reduced in the bottomside F region and plasma bubbles and spread F irregularities develop in the region of magnetic equator. Regardless of the longitudinal location, the forward plasma fountain and the equatorial anomaly become symmetric with respect to the magnetic equator and plasma bubbles appear in the trough region of the anomaly (Balan and Bailey, 1995 and Balan et al., 1997a,b). TOPEX data shows this stage of the development including bubble formation (see Figure 3(a)). At this time no TEC build up is detected at Southern mid latitudes.

Soon after the prereversal strengthening, the upward **ExB** field becomes downward directed and the plasma fountain begins its operation in the opposite direction. The downward drift pushes the plasma down across the horizontal magnetic field lines, which creates low plasma pressure in the topside ionosphere. As a response to the generation of the low plasma pressure region in the topside ionosphere, the plasma starts flowing towards the magnetic equator from both of the high-pressure crests to fill up the low-pressure region, and the process goes on until the intensity of downward drift decreases. This mechanism is called reverse fountain, which is the main source of plasma for the nighttime increases centered on the magnetic equator. At the time of reversal when the F region **ExB** drift becomes downward directed the vertical **ExB** drift velocity quickly increases and changes with time, and therefore the neutral wind has the least effect upon the reverse fountain (Balan and Bailey, 1995 and Balan et al., 1997a). The downward plasma flow provides favorable conditions for the generation and propagation of plasma bubbles and spread F irregularities. In this study a symmetric nighttime peak centered on the magnetic equator with plasma bubbles was recognized from TOPEX data (see Figures 3((d)). The occurrence of a well-developed TEC build up at Southern mid latitudes is evident.

Soon after the **ExB** drift became downward directed it reaches its maximum at around 2100 LT (Balan and Bailey, 1995 and Balan et al., 1997a,b). During this period the neutral wind does not alter the symmetry of the reverse fountain with respect to the geomagnetic equator. Consequently the nighttime peak developed at the geomagnetic equator is symmetric. TOPEX data illustrate this stage of the development (see Figures 3(e) and 3(g)). The occurrence of a significant nighttime increase at Southern mid latitudes is clearly visible.

Figure 4(a) shows the direct comparison of two (a forward and a reverse) fountain related formations and the opposite phase indicates that the mechanisms underlying their creation are opposite. The significant TEC build up at -39° magnetic latitude alongside the large equatorial nighttime increase is clearly indicated. The model results of Balan and Bailey (1995) have shown that the low latitude nighttime increase is due to the large downward flow and the reverse plasma fountain provides the necessary extra ionization. TOPEX results of this study suggest that the mid-latitude nighttime increase (Λ=-39°) could be also a reverse-fountain-related formation. As there was no mid-latitude nighttime increase observed in this region during the period of prereversal strengthening, that is a forward fountain related process, the reverse plasma fountain might be responsible alone. This suggestion can be supported by the comparison of two reverse-fountain-related formations developed at around the time of reversal and at the time of maximum drift velocity (see Figure 4(b)). The TOPEX data reveal that the significant nighttime increase was already well formed soon after the time of reversal. This suggests that the mid-latitude nighttime increase might form soon after the vertical drift became downward directed. Its

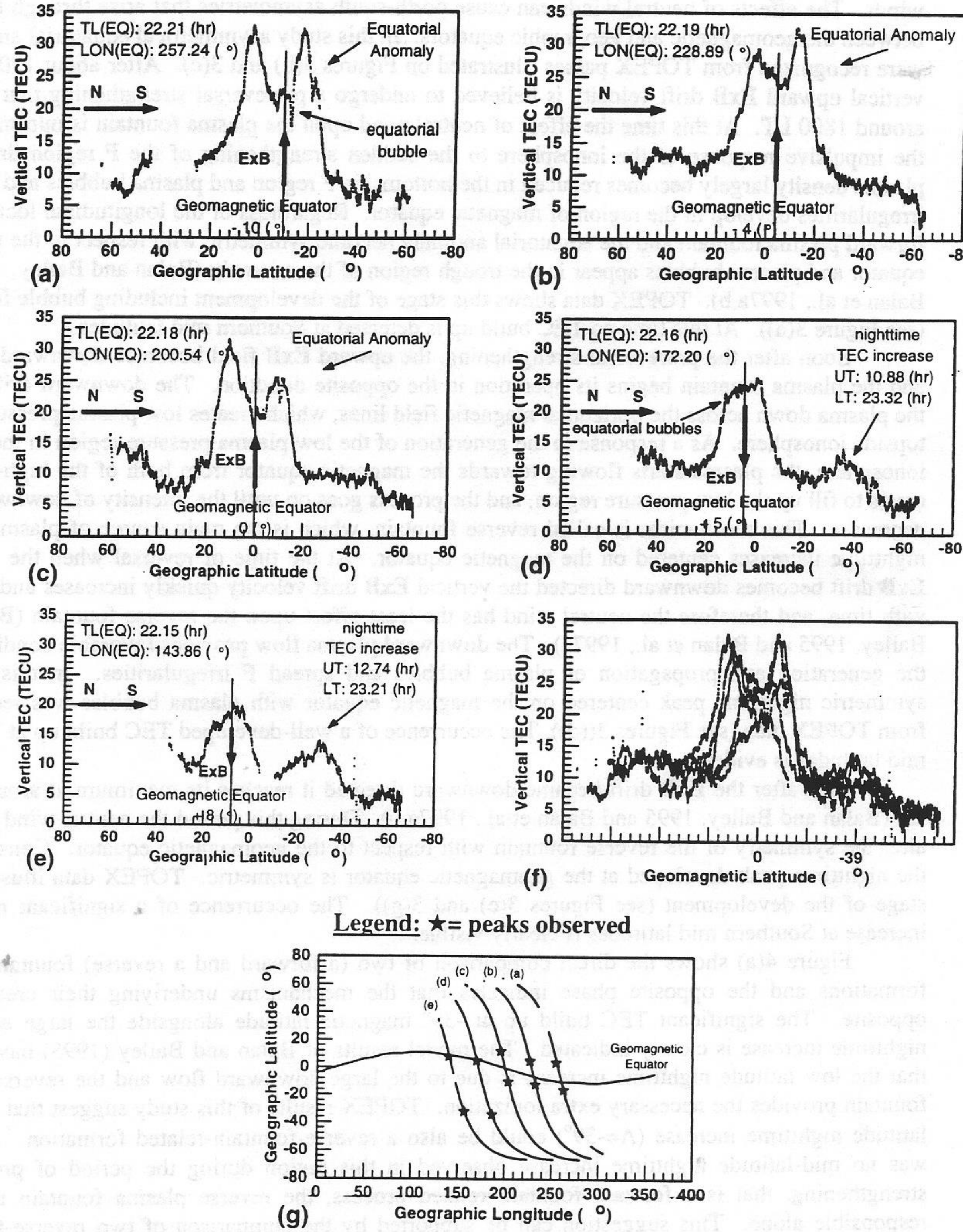

Figure 3. TOPEX passes depict the equatorial anomaly ((a),(b) and (c)), and nighttime TEC enhancements ((d) and (e)) on the 24th of April 95. Passes centered around the geomagnetic equator illustrate the magnetic alignment of these formations (f). Map of satellite tracks denotes the positions of the peaks and the geomagnetic equator (g).

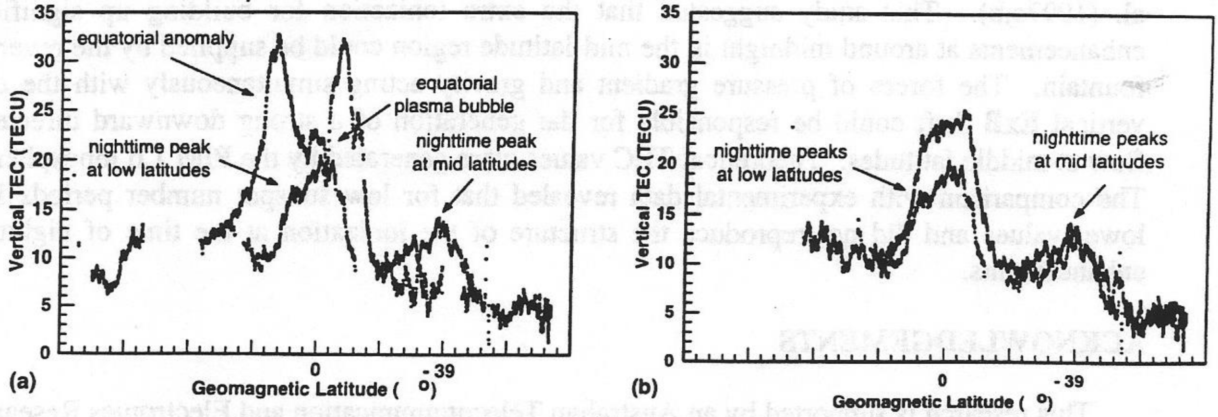

Figure 4. (a) Comparison of the equatorial anomaly with a plasma bubble at the time of the prereversal strengthening and nighttime peaks at low and mid latitudes after the time of reversal on the 24th of April 1995. (b) Comparison of nighttime peaks at low and mid latitudes after the time of that reversal from Figures 3(d) and 3(e).

development seems to be the direct consequence of the low latitude processes taking place at around the time of reversal and therefore the main source of plasma could be the reverse fountain. An explanation is put forward here that describes the possible mechanisms that might take place at mid latitudes. According to this, in the reverse fountain the plasma from the crest could flow also away from the magnetic equator. Forces of pressure gradient and gravity could generate and keep the downward field aligned plasma flow going from both of the high-pressure crest regions towards the low-pressure mid-latitude regions of both hemispheres. This process is coupled with the combined effects of neutral wind and the angle of declination. The overall dominating mechanism could obstruct or assist the development of a mid-latitude nighttime peak in one hemisphere. As Su et al. (1994) explained, at nighttime the equatorward neutral wind can impede the F region field aligned plasma flow or rise the F region plasma to altitudes of lower chemical loss in order to maintain high TEC values in the nighttime sector even after midnight. As is seen from the results presented in this paper, the nighttime peak was not always symmetric. As a net result of all the contributing factors, the occurrence of mid-latitude nighttime increase has a strong longitudinal dependence that determines its rate of development and spatial distribution in a global scale. Note also the reversal occurs earlier in Western Pacific where the magnetic equator is located north of the geographic.

CONCLUSION

The results of this study indicate that the combination of dual-frequency GPS and TOPEX techniques provide an effective way of investigating the upper atmosphere. Different methods of plotting the TEC were used to investigate various ionospheric irregularities such as the equatorial anomaly, equatorial plasma bubbles and nighttime TEC enhancements. The nighttime increases in TEC were recognized on daily and hourly GPS plots. The seasonal variation was investigated and it was found that the premidnight peak is persistent and well developed throughout the year, while the postmidnight peak is less developed in the season of vernal equinox and absent in summer. The GPS investigation was augmented with the TOPEX technique and the correspondence in results confirmed the GPS findings. The TOPEX findings showed a good agreement with the model results of Balan and Bailey (1995) and Balan et al. (1997a,b) related to the equatorial anomaly, plasma fountains (both forward and reversed) and the low latitude nighttime increase. An explanation of the physical processes that may be responsible for the formation of the premidnight TEC enhancement at mid latitudes is proposed in terms of the diffusion theory by Balan and Bailey (1995) and Balan et al. (1997a,b). This study suggested that the extra ionization for building up significant TEC enhancements at around midnight in the mid-latitude region could be supplied by the reverse plasma fountain. The forces of pressure gradient and gravity acting simultaneously with the downward vertical **ExB** drift could be responsible for the generation of a strong downward directed plasma flow at middle latitudes. Theoretical TEC values were generated by the PIM 1.6 ionospheric model. The comparison with experimental data revealed that for low sunspot number periods PIM gave lower values and did not reproduce the structure of the ionization at the time of nighttime TEC enhancements.

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