On TIE-GCM simulation of the evening equatorial plasma vortex

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It has already been shown that the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) is capable of reproducing the pre-reversal enhancement (PRE) of the equatorial zonal electric field. However, the ability of TIE-GCM to reproduce the post-sunset plasma vortex, an important feature of the evening equatorial ionosphere closely related to the PRE, has been overlooked and had yet to be addressed. In order to address the ability of TIE-GCM to reproduce the vortex, we examined model simulations of the plasma flow pattern in the geomagnetic equatorial plane and compared the simulations with ground-based radar observations. We found that TIE-GCM is indeed capable of reproducing the overall features of the post-sunset equatorial plasma vortex pattern. We also found that both E and F region dynamos in TIE-GCM dictate the main features of the vertical shear in the zonal plasma drifts that is part of the evening vortex. The contribution of vertical currents to the shear, however, is not negligible. Comparison of simulation results with radar measurements of the vortex indicates that the model can still be improved to better match the observations.


1. Introduction

An important feature of the low-latitude equatorial ionosphere is the so-called post-sunset equatorial plasma vortex [e.g., Haerendel et al., 1992; Eccles et al., 1999; Kudeki and Bhattacharyya, 1999]. The plasma vortex is formed by a nearly circular flow of ionospheric plasma in the geomagnetic equatorial plane. Observations show that, in the hours following sunset, the ionospheric plasma around the F region peak and above generally moves in the eastward direction, at least during geomagnetically quiet conditions. The plasma in the bottomside F region, on the other hand, tends to move in the westward direction. This creates a vertical shear in the equatorial zonal plasma flows [e.g., Kudeki et al., 1981; Tsunoda et al., 1981]. During the pre-reversal enhancement (PRE) of the zonal electric field, the motion of the plasma is predominantly upward. At later times, however, the motion has a dominant component in the downward direction. This circulation pattern is in the clockwise direction (looking North) when visualized on maps of ionospheric drifts as a function of altitude and local time such as those constructed with Jicamarca radar observations [Kudeki and Bhattacharyya, 1999].

The equatorial plasma vortex has been studied, mostly, experimentally with a few notable exceptions [e.g., Haerendel et al., 1992; Eccles et al., 1999]. Most of the experimental studies of the vortex used ground-based radar observations [Tsunoda et al., 1981; Kudeki et al., 1981; Kudeki and Bhattacharyya, 1999] but satellite in-situ observations [Eccles et al., 1999] and experiments using chemical releases [Valenzuela et al., 1980] have also been used to study the dynamics of the drifts in the post-sunset equatorial ionosphere. Using the East–west scans of the equatorial ionosphere by the ALTAIR incoherent scatter radar (Kwajalein Atoll in the Pacific sector) and equatorial spread F structures as tracers of background plasma motion, Tsunoda et al. [1981] identified a vertical shear in the horizontal (zonal) plasma motion of the ionosphere. They also pointed out that this shear, when connected with the vertical motion of the plasma during evening hours, would form a vortex-like pattern. Using interferometric coherent backscatter radar observations of F region irregularities, Kudeki et al. [1981] also found a vertical shear in the zonal plasma velocity in the Peruvian longitude sector. Almost two decades later, improved coherent and incoherent scatter radar observations [Kudeki et al., 1999] at the Jicamarca Radio Observatory allowed Kudeki and Bhattacharyya [1999] to clearly identify vortex-like patterns formed by the measured zonal and vertical drifts of the equatorial plasma. Furthermore, the improvement in the radar observations allowed monitoring of the behavior of the ionospheric plasma density...
and of equatorial spread \( F \) (ESF) irregularities during the development of the vortex. Kudeki and Bhattacharyya [1999] noticed that the development of ESF radar plumes seemed to be, somehow, connected with the development of the vortex. In recent years, renewed attention has been given to the equatorial plasma vortex. This is, mostly, because of recent findings relating the vertical shear in the zonal plasma flow, and the development of equatorial spread \( F \) (ESF) [Kudeki and Bhattacharyya, 1999; Hysell and Kudeki, 2004; Kudeki et al., 2007]. Therefore, the equatorial plasma vortex is an exciting and important feature of low-latitude ionosphere electrodynamics. Prediction of the equatorial vortex by numerical ionospheric models indicates that a realistic representation of the low-latitude ionospheric dynamics is being produced. Furthermore, a better understanding about the importance of different sources capable of contributing to the shear is still a current subject of investigation [e.g., Hysell et al., 2005].

[4] The Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) is a complex, time-dependent model of the upper atmosphere. It is one of the few models capable of resolving the dynamics of the neutral thermosphere and ionosphere self-consistently. This self-consistency is important as winds and plasma drifts can affect each other significantly [e.g., Richmond et al., 1992].

It has been shown that TIE-GCM can produce realistic patterns of the equatorial \( F \) region plasma vertical drifts in the equatorial ionosphere [Fesen et al., 2000]. Fesen et al. [2000] showed that local time variation of the height-averaged \( F \) region drifts including the PRE predicted by TIE-GCM was in good agreement with observations made by the Jicamarca incoherent scatter radar. This agreement, however, required some adjustment in the nighttime \( E \) region density and in the amplitude and phase of atmospheric tides. The results of Fesen et al. [2000] have motivated the use of TIE-GCM to investigate the electrodynamics of the low-latitude ionosphere, in particular the variability of the vertical plasma drifts, one of the main drivers of the low-latitude ionosphere [e.g., Vichare and Richmond, 2005; Fang et al., 2008a, 2008b]. Despite its importance, however, the equatorial plasma vortex seems to have been overlooked in TIE-GCM studies of the equatorial plasma drifts.

[5] Recent results relating the plasma vortex and the development of ESF motivated us to revisit TIE-GCM simulations to investigate whether this model is able to predict a more complete picture of the plasma flow pattern in the equatorial region around sunset hours. Here, we present a short report of simulations of zonal and vertical equatorial plasma drifts produced by TIE-GCM, which were used to address the overlooked ability of this model to reproduce the post-sunset equatorial plasma vortex. We also present further analysis of the vertical shear in the zonal plasma drifts that is part of the vortex. This article is organized as follows. In section 2 we provide a brief description of the model, and describe the geophysical conditions we have considered in the simulations used for this study. In section 3, we present and briefly discuss the results of the simulations. A more detailed discussion of the results including analysis of local and field-line integrated parameters, and a comparison of the model predictions with observations is presented in section 4. Section 5 presents a summary of our findings and final remarks.

2. Model Description

[6] Since the early 80’s, the National Center for Atmospheric Research (NCAR) has been developing a series of three-dimensional general circulation (GCM) models of the Earth’s upper atmosphere [Dickinson et al., 1981, 1984]. Recent versions of these models include the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM), which has been used to investigate the low-latitude ionospheric electrodynamics [e.g., Richmond et al., 1992; Fesen et al., 2000; Fang et al., 2008a, 2008b]. TIE-GCM is a three-dimensional, time-dependent model, which solves the full dynamical equations of the coupled thermosphere and ionosphere self-consistently [Richmond et al., 1992; Fang et al., 2008b]. The main parameters for specification of TIE-GCM simulation runs are: (a) the solar input, (b) the magnetospheric input, and (c) atmospheric tides at the lower boundary.

[7] The solar input for TIE-GCM is based on the EUVAC empirical model Richards et al. [1994]. EUVAC represents the solar irradiance and its variability. The variability is parameterized by solar flux indices such as \( F_{10.7} \). The magnetospheric input in TIE-GCM consists of the specification of the high-latitude convection pattern and the specification of the aurora. Convection models readily available for TIE-GCM runs are the Heelis [Heelis et al., 1982] and the Weimer 2005 [Weimer, 2005] models. The auroral model available for TIE-GCM is the one described by Roble and Ridley [1987]. Finally, the lower boundary conditions (around 97 km altitude) of TIE-GCM must be specified. There, a constant neutral temperature of 181 K is used and zonal and neutral winds are set to zero. However, tidal perturbations can be added in. While the tidal perturbations can be specified using Hough Modes [e.g., Fesen et al., 2000], they are usually specified by the Global Scale Wave Model (GSWM) [Hagan and Forbes, 2002, 2003].

[8] Given the specification of the various inputs, the TIE-GCM computes various physical parameters of the neutral and ionized upper atmosphere self-consistently. These parameters include thermospheric neutral winds and ionospheric \( E \times B \) plasma drifts, neutral and ion densities, composition and temperatures. At low and midlatitudes, the TIE-GCM computes the electric potential from the wind-driven dynamo. In addition to wind-driven currents, pressure-gradient-driven and gravity-driven currents are also taken into account. The electric potential calculations are made in magnetic apex coordinates [Richmond, 1995] using a realistic model of the geomagnetic field (IGRF). The potential calculations assume that the geomagnetic field lines are equipotential.

2.1. Simulation Conditions

[9] For this study, we used simulations whose input parameters were chosen so as to represent equinoctial conditions (day of year 80) for year 2002, when the solar activity was considered high \((F_{10.7} = 220 \times 10^{-22} \text{ W/m}^2/\text{Hz})\). All the simulations were carried out using version 1.94.1 of TIE-GCM. In order to simulate geomagnetically quiet conditions,
we specified a hemispheric power of precipitating auroral particles of 3 GW and a cross polar cap potential of 30 kV. We used the Heelis model for the high-latitude convection pattern. The simulation conditions (equinox and geomagnetically quiet) were chosen to maximize the development of the pre-reversal enhancement of the equatorial zonal electric field over a wide range of longitudes [Scherliess and Fejer, 1999; Fejer et al., 2008]. In addition to this study, the simulations presented here were also produced for a separate investigation of the low-latitude electrodynamics that required the specification of high solar flux conditions. The results of this separate study will be presented elsewhere. Atmospheric tides were specified using GSWM. Only diurnal and semi-diurnal migrating tides were considered. The TIE-GCM runs had a spatial resolution of 5° in longitude, 5° in latitude, and 2 grid points per scale height. Note, however, that the geomagnetic grid has a higher resolution to better solve the electrodynamics, particularly, in the equatorial electrojet region. Simulation results were saved every 10 min.

3. Results

[10] In the present study, we are interested in TIE-GCM predictions of the height (and temporal) variability of the zonal and vertical components of the plasma velocity over the geomagnetic equator. As a reference, Figure 1 shows the location of the magnetic equator, at 150 km altitude, as a function of geographic longitude and latitude for 2002. The location of the magnetic equator varies slightly with altitude, and we have taken into account this height variability in our analysis. The zonal velocity we refer to in our results corresponds to the plasma drift component in the geomagnetic zonal direction since we are interested in the two-dimensional pattern of the plasma vortex in the geomagnetic equatorial plane.

3.1. Variability of Zonal and Vertical Plasma Drifts Predicted by TIE-GCM

[11] Figure 2 shows examples of the global zonal and vertical plasma drifts predicted by the TIE-GCM simulation over the magnetic equator, as a function of longitude and altitude for three different times (0400, 01200 and 1800 UT). Local times are also indicated on top of each panel. Figure 2 (left) shows the variability of the vertical (upward) drifts ($W_i$). As expected, the vertical drifts are upward in the daytime sectors and downward in the nighttime sectors. During daytime, the magnitude of the drifts is usually less than 25 m/s. In the post-sunset period, however, the drifts can exceed 40 m/s. The enhancement of the drifts before their reversal from upward to downward can be observed as the bright red vertical band in each panel. The pre-reversal enhancement (PRE) of the drifts occurs around $-140^\circ$E, $100^\circ$E, and $-20^\circ$E in the 0400, 1200 and 2000 UT examples, respectively. Therefore, the PRE occurs around 18:30–19:00 LT in each longitude sector. This is in good agreement with climatological curves of the vertical plasma drifts for high solar flux conditions [e.g., Scherliess and Fejer, 1999; Fejer et al., 2008]. A more detailed inspection of the local time variation of the vertical drifts shows that the PRE occurs at slightly different local times in each longitude sector. We also must point out that the magnitude of the PRE varies with longitude. The variability of the PRE during equinoctial conditions was studied by Vichare and Richmond [2005] using MTIE-GCM [Peymirat et al., 1998], an extension of TIE-GCM that includes the coupling between the inner magnetosphere (M) and ionosphere. They found that MTIE-GCM predicts PRE values in the American-Atlantic sector that are larger than in the East Asian-Pacific. The MTIE-GCM simulations are in good agreement with observational results. Our simulation results also show a similar longitudinal variability for the vertical drifts.

[12] Figure 2 (right) shows the zonal (eastward) plasma drift ($U_i$) results. Again, as expected, the drifts are mostly

![Figure 1. Map showing the location of the geomagnetic equator (dashed line).](image-url)
westward in the daytime sectors and eastward in the nighttime sectors. The most striking feature in these examples is the strong vertical shear in the zonal plasma drifts observed after sunset. Around sunset hours and below approximately 300 km altitude, the plasma moves in the westward direction, while the plasma above this altitude moves in the eastward direction. This feature resembles very much the observations of plasma drifts made by the Jicamarca incoherent scatter radar in the equatorial region [e.g., Kudeki and Bhattacharyya, 1999].

The altitude where the zonal drifts reverse from westward to eastward varies with longitude. This is most evident when comparing the zonal drifts for 0400 UT and 2000 UT in Figure 2.

3.2. The Vortex Pattern

Figure 2 illustrates the variability of the zonal and vertical drifts and shows that our runs indeed produce realistic plasma drifts that are, at least qualitatively, in agreement with previous theoretical and experimental studies. The altitude-longitude variability of the zonal and vertical drifts seen in Figure 2 also gives a first indication that TIE-GCM is able to reproduce the equatorial plasma vortex.

We now combine the results presented in Figure 2 to produce a graphical representation that will better show the development of a vortex-like structure in the geomagnetic equatorial plane. Figure 3 shows the behavior of the plasma flow in the magnetic equatorial plane for the same three times shown in Figure 2. The examples show the development of a vortex pattern centered around –130°E, 120°E, and 10°E for 0040 UT, 1200 UT and 2000 UT, respectively. The vortex patterns shown in Figure 3 resemble very much the patterns obtained by Kudeki and Bhattacharyya [1999] using incoherent scatter radar observations, and the patterns constructed by Eccles et al. [1999] using in-situ observations of the ionospheric drifts made by the San Marco satellite.

Figure 3 also shows a longitudinal variability in the morphology of the vortex pattern. For the 0400 UT panel, for instance, the vortex is centered at around 275 km altitude. In the other two cases shown in Figure 3, however, the pattern is centered at an altitude between 300 and 350 km.

3.3. Local Time Variation of the Vortex Pattern

The flow patterns obtained by Kudeki and Bhattacharyya [1999] and Eccles et al. [1999] were presented using the variability of the drifts as a function of height and local time. Kudeki and Bhattacharyya [1999], however, claimed that, because of the long timescale of the processes involved in the development of the vortex, the LT vs height maps obtained with ground-based radar observations would represent well the variation of the drifts as a
function of longitude. The model results in Figure 3 indicate that, indeed, the vortex pattern can be observed as a function of longitude as argued by Kudeki and Bhattacharyya [1999].

[18] Figure 4 shows the variability of the vertical and zonal plasma drifts as a function of local time that better represents what has been measured with ground-based radars. The local time variation of the drifts in Figure 4 is for the longitude sector of Jicamarca (75°E) and for the time range of interest here, that is, around sunset hours. Again, Figure 4 (top) shows that the plasma moves in the upward direction during daytime and then starts to move in the downward direction at approximately 1930 LT. The sunset at E region heights occurs around 1810 LT for the coordinates of the Jicamarca site on this day. The PRE develops between 1800 LT and 1930 LT, with maximum velocities occurring around 1845 LT.

[19] Figure 4 (middle) shows the zonal (eastward) plasma velocity variation predicted by TIE-GCM for the Jicamarca sector. At F region heights (above ~300 km) the zonal velocity of the plasma starts to reverse its direction, from westward to eastward during daytime, and fully reverses direction around 1800 LT. Note that the zonal deceleration of the plasma, before 1800 LT, seems to follow the deceleration in the vertical plasma velocity. Around 2000 LT, the zonal plasma drift around the F region peak reached its maximum eastward velocity, close to 150 m/s. The zonal plasma velocity below 300 km, however, only decelerates until around 1600 LT and maintains its westward velocity of about 50 m/s until approximately 1730 LT. After that time the westward plasma velocity increases again and reaches over 100 m/s at about 1900 LT. The zonal plasma velocity in the bottomside F region (below 300 km) only starts to move in the eastward direction after 2000 LT.

[20] Similar to Figure 3, Figure 4 (bottom) shows two-dimensional vectors of the plasma velocity. The plasma flow modeled by TIE-GCM exhibits a vortex pattern, similar to those measured by Kudeki and Bhattacharyya [1999] and Eccles et al. [1999], that is, it shows the development of a circular (clock-wise) flow pattern centered around 1930 LT and at approximately 275–300 km altitude.

4. Discussion

[21] In order to better understand the origin and dynamics of the vortex simulated by TIE-GCM, we examined, in more detail, the local time variation of various thermospheric and...
Figure 5. Simulation results for Peruvian sector: (a) zonal thermospheric winds, (b) field-line integrated Pedersen conductivities and electrostatic potential (in kV), and (c) vertical plasma drifts. The dashed white line in Figure 5c indicates the variation of the height-averaged vertical plasma drift. The solid thick lines are the axes. The vertical axis varies from −60 m/s to 60 m/s as indicated on the right-hand side of the panel. (d) The zonal (eastward) plasma drifts.

4.1. Insights on the Dynamics of the Vortex Simulated by TIE-GCM

Figure 5 shows the variability of zonal winds, field-line integrated Pedersen conductivities, electric potential, and vertical and zonal plasma drifts for the Peruvian sector (−75°E) as predicted by TIE-GCM. The results in Figure 5 are from the same simulation run (for March 2002) whose outputs were shown in previous figures. We focus, however, on the thermospheric and ionospheric variability during the vortex development (around and following sunset hours).

Figure 5a shows the variability of the local thermospheric zonal winds at the magnetic equator as a function of local time and height. Figure 5b shows the field-line integrated Pedersen conductivities ($\Sigma_P$). Significant integrated conductivities are seen before ~1800 LT (E region sunset). The conductivities, however, start to drop substantially after 1800 LT as a result of photochemical and transport processes. Figure 5b also shows iso-contours of the electric potential obtained by the TIE-GCM potential solver. Figure 5c shows the variability of the vertical plasma drifts at the magnetic equator. In addition, a thick dashed white line also indicates, for reference, the temporal variation of the height-averaged vertical plasma drifts for reference. The vertical and horizontal thick solid lines represent the axes for the averaged drifts. The vertical axis varies from −60 m/s to 60 m/s. Finally, Figure 5d shows the zonal plasma drifts predicted by TIE-GCM.

TIE-GCM simulation results show two distinct and well-defined regimes in the equatorial ionospheric plasma dynamics. The first regime occurs before and around local sunset (~1800 LT). During that time, E region Pedersen conductivities are significant and the E region wind dynamo plays an important role in the generation of the equatorial electric fields. The resulting zonal and vertical electric fields drive upward and westward plasma drifts in the equatorial $F$ region. The second regime occurs well after sunset (say after 2000–2100 LT), when the E region conductivities reached their minimum steady state values and can be considered negligible compared to the $F$ region conductivities (see Figure 5b). During that time, the $F$ region dynamo dominates. Vertical and zonal plasma drifts are in the downward and eastward directions, respectively.

The simulations also show that the evening vortex develops during a period of transition between the two regimes described above, between about 1800 LT and 2100 LT. The PRE peak occurs around 1900 LT and the strongest drifts in the zonal plasma drifts is observed around 1930 LT. The simulation results suggest that the PRE is a transient response to the increasing wind-driven vertical current in the $F$ region right after local sunset. During that time, the E region conductivity is decreasing significantly and can no longer fully close the current loop in the magnetic meridian. Supposedly, the zonal electric field would be enhanced (PRE) to provide at least some of the current demanded by the wind-driven dynamo in the $F$ region. The vertical drifts caused by the eastward electric fields, including the PRE, near sunset hours cause a large upward motion of the plasma, which is part of the vortex pattern.

A better understanding of the vertical shear in the zonal plasma, that is another important part of the evening vortex, requires an examination of the main sources of the vertical electric fields during the transition period between 1800 LT and 2100 LT. At the magnetic equator, the vertical polarization electric field at $F$ region heights can be described by [Haerendel et al., 1992]:

$$E_L = -BU\phi + \frac{\nabla H}{\Sigma_p} + J_L \nabla \phi$$

where subscripts $L$ and $\phi$ indicate components in the vertical and zonal (eastward) directions, respectively, $E$ is the electric field, $\Sigma_p$ and $\Sigma_H$ are the field-line integrated Pedersen and Hall conductivities, respectively, $B$ is the geomagnetic field, and $U_{\phi}$ is the field-line integrated, Pedersen
conductivity weighted zonal wind. Equation (1) indicates that the vertical polarization electric field \( \mathbf{E} \) has three main sources: (a) the wind-driven dynamo, (b) Hall currents driven by zonal polarization electric fields, and (c) vertical currents (\( \mathbf{J}_L \)) resulting of the divergence of the horizontal currents \( \mathbf{J}_f \) [Haerendel et al., 1992].

Equation (1) can be written in terms of zonal and vertical \( \mathbf{E} \times \mathbf{B} \) plasma drifts:

\[
U_i = U_p^\rho - \frac{\Sigma_H \Sigma_p^{-1} W_i}{\Sigma_p} - \frac{\mathbf{J}_L}{\Sigma_p^2} \tag{2}
\]

where, \( U_i \) and \( W_i \) are the zonal and vertical plasma drifts. Figure 6 summarizes the results of our analysis on the importance of the three terms in the right-hand side of equation (2). Figure 6a shows the contribution to the plasma drifts from field-line integrated, Pedersen conductivity weighted zonal winds, while Figure 6b shows the contribution from the Hall currents. Figure 6c shows the combined contribution of both wind-dynamo and Hall currents. Finally, Figure 6d reproduces the equatorial zonal plasma drifts simulated by TIE-GCM for comparison purposes. The results in Figure 6 indicate that the main features of the equatorial zonal plasma drifts simulated by TIE-GCM, including the vertical shear during the vortex, are mostly driven by the wind dynamo term (compare Figures 6a and 6d). When the Hall and wind dynamo terms are combined, the morphology of the zonal drifts predicted by TIE-GCM is reproduced almost exactly (compare Figures 6c and 6d), with only a small difference in the magnitude of the drifts, which is indicative of a non-negligible contribution from the vertical (\( \mathbf{J}_L \)) current term.

Finally, we analyzed the individual contributions from the \( E \) and \( F \) region dynamos to the simulated zonal
plasma drifts during the evening vortex. Figure 7 shows the results of this analysis. It shows the E (below 150 km) and F (above 150 km) region contributions to the field-line integrated, conductivity weighted zonal wind. Figure 7c shows the contribution from both regions, $U_{\phi}^{PE}$. These results show that, during the transition time after sunset, when the vortex develops, the E region dynamo still contributes significantly to the shear in the zonal plasma drifts simulated by TIE-GCM. Haerendel et al. [1992] suggested that $U_{\phi}^{PE}$ could make a significant contribution to the vertical polarization electric field but predicted this contribution to be limited to heights below 200 km. Our analysis of TIE-GCM simulations show that $U_{\phi}^{PE}$ can contribute more. Figure 7a shows that $U_{\phi}^{PE}$ is far from negligible (say ≥ 20 m/s in the westward direction) at an apex height as high as 275 km.

4.2. Comparison With Observations

Kudeki and Bhattacharyya [1999] presented two examples of ionospheric drift measurements made with the Jicamarca incoherent scatter radar where the evening vortex can be clearly identified (Plates 1 and 2 in their paper). These examples are reproduced here in Figure 8 to help the reader in our comparison exercise. Figure 8 shows the Range-Time-Intensity (RTI) maps of the echoes observed by the Jicamarca radar on February 24, 1996 and April 8, 1997. Greenish tones indicate incoherently scattered echoes from thermal electron density fluctuations in the quiescent ionosphere. The red-to-purple regions indicate coherently back-scattered echoes from field-aligned electron density irregularities. The coherent echoes in the RTI maps indicate the occurrence of bottom-type layers followed by topside layers (radar plumes). The bottom-type layers are vertically narrow echoing regions located at bottomside F region heights. Note that bottom-type layers are confined in a region of westward (or small) plasma drift. Radar plumes are vertically well developed echoing regions that reach the topside ionosphere. Radar plumes are interpreted as the manifestation of equatorial spread F electron density depletions. The arrows superimposed on the RTI maps indicate the direction of the ionospheric plasma drifts.

Similar to the simulations presented here, a vortex-like pattern in the measured drifts can be clearly identified. A closer inspection of these observations indicates the occurrence of small, secondary vortices that could be associated with plasma perturbations caused by the development of ionospheric irregularities. On February 24, 1996 the vortex measured by Jicamarca was centered around 1940 LT and about 300 km altitude. On April 8, 1997, however, the vortex occurred earlier, around 1920 LT but around the same altitude (300 km). The vortex simulated by TIE-GCM over Jicamarca (for March 21 of 2002) was also centered around 300 km altitude. The local time of the simulated vortex was 1930 LT (see Figure 4). The good agreement between these observations and our simulation results, however, might be somewhat deceiving. We must point out that the measurements presented by Kudeki and Bhattacharyya [1999] were made under much smaller solar flux conditions (F10.7 ~ 76) than those considered in our simulations (F10.7 ~ 220).
Therefore, for completeness, we also performed and examined TIE-GCM simulations for solar flux conditions similar to those under which Jicamarca made the observations. Figure 9 shows the vertical and zonal plasma drifts simulated by TIE-GCM for February 24, 1996 and April 8, 1997. It also shows the two-dimensional plasma flow pattern created under those conditions (Figure 9, bottom). It is clear that, for low solar flux conditions, the magnitude of the PRE predicted by TIE-GCM is much lower than that predicted for high solar flux conditions (see Figure 4). The increase of the PRE magnitude with solar flux is in qualitative agreement with observations [e.g., Fejer et al., 1991]. Moreover, the magnitude of the nighttime zonal drifts is also greatly reduced during low solar flux conditions, also in agreement with observations [Fejer et al., 1991]. Despite the decrease in the magnitude of the drifts during low solar flux conditions, a vortex-like pattern can still be identified on both days. A reduction in the solar flux conditions does not seem to affect much the central altitude of the vortex. We noticed, however, that TIE-GCM predicts the center of the vortex to occur at earlier times when low solar flux conditions are considered. Figure 9 shows that the center of the simulated vortex occurs around 1900 LT on both February 24, 1996 and April 8, 1997. Jicamarca measurements showed the vortex occurring around 1920 LT and 1940 LT on February 24, 1996 and April 8, 1997, respectively.

It is not surprising, however, that the features predicted by TIE-GCM do not exactly match the dynamics measured by Jicamarca on specific dates. TIE-GCM results should be interpreted as a representative of the average electrodynamics. The Jicamarca measurements (shown in Figure 8), on the other hand, represent realizations of electrodynamic processes with high day-to-day variability. A better assessment of TIE-GCM measurements would require climatological estimates of the vortex based, perhaps, on long-term, quiet time measurements made by the Jicamarca radar. Furthermore, it is possible that adjustments in model parameters need to be made to produce simulations that better match specific conditions. Simulations of the PRE alone, for instance, required adjustments so that model results could better match the measurements [Fesen et al., 2000]. Fesen et al. [2000] found better agreement between the simulations of the equatorial drifts and measurements by reducing the values of $E$ region densities in the evening sector. Our results indicate that similar adjustments in TIE-GCM might be necessary so that model results of the plasma vortex better match the observations. The adjustments for a better agreement between the simulations and measurements vortex pattern are outside the scope of this study. We believe, however, that the adjustments are unlikely to be limited to $E$ region densities only.

5. Summary and Final Remarks

The so-called post-sunset equatorial plasma vortex is a two-dimensional pattern in the flow of ionospheric plasma that has been observed in the geomagnetic equatorial plane. The vortex is a manifestation of complex electrodynamic processes taking place in the equatorial ionosphere during sunset and post-sunset hours. Recently, the retrograde zonal plasma flow in the bottomside $F$ region with respect to the thermospheric wind direction has been associated with the development of underlying ionospheric perturbations and with the development and morphology of equatorial spread $F$ [Hysell and Kudeki, 2004; Kudeki et al., 2007]. Therefore, the reproduction of the vortex by numerical models is an indication that important processes taking place in the equatorial thermosphere/ionosphere are being captured. This
is particularly important for general circulation models, where the thermosphere/ionosphere is solved self-consistently, meaning that the feedback from the ionosphere is taken into account in the dynamics of the neutral upper atmosphere.

It has already been shown that the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) is capable of reproducing the pre-reversal enhancement (PRE) of the equatorial zonal electric field [Fesen et al., 2000]. However, the ability of TIE-GCM to reproduce the post-sunset plasma vortex had been overlooked and had yet to be addressed. In order to address the ability of TIE-GCM to reproduce the vortex, we examined the model simulations of the plasma flow pattern in the geomagnetic equatorial plane and compared the simulations with measurements made by the Jicamarca incoherent scatter radar [Kudeki and Bhattacharyya, 1999]. In addition, we examined the behavior of the thermospheric winds and conductivities in order to better understand the sources and dynamics of the vortex predicted by TIE-GCM.

We found that TIE-GCM is, indeed, capable of reproducing the overall features of the post-sunset equatorial plasma vortex pattern. The simulations clearly show the development of the vortex pattern in the ionospheric plasma drifts over the Jicamarca location and at various other longitude sectors. We also analyzed local and field-line integrated parameters to better understand the variability of the drifts forming the vortex simulated by TIE-GCM. In particular, we examined the sources of the vertical shear in the zonal plasma drifts. We found that the wind dynamo contributes the most to the shear simulated by TIE-GCM, but the contribution from vertical currents is also significant and cannot be neglected. Finally, further analyses also showed that the \( E \) region dynamo plays an important role in the development of the shear.

Despite the fact that TIE-GCM can reproduce the overall features of the vortex, we found that improvements in the model can be made so that the simulations better match the observations. The model predicts the center of the

![Figure 9. TIE-GCM simulation results of (top) vertical and (middle) zonal ionospheric drifts over the Peruvian \((-75^\circ E)\) sector for solar-flux conditions similar to those of (left) February 24, 1996 and (right) April 8, 1997. (bottom) The two-dimensional representation of the ionospheric drifts.](image)
vortex to occur earlier than what has been measured. We suspect that not only better estimates of the conductivities predicted by TIE-GCM are needed but also a better assessment about the correctness of thermospheric wind predictions. Finally, we also believe that would be clarifying to evaluate the response of the plasma vortex to varying patterns in the zonal component of the thermospheric wind. This task, however, is less than straightforward and will be the subject of a future, more comprehensive investigation.

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