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Influences of geomagnetic fields on longitudinal variations of vertical plasma drifts in the presunset equatorial topside ionosphere

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[1] On the basis of the measurements from the ion drift meter on the Defense Meteorological Satellite Program F13 Satellite from 2000 to 2002, the relative longitudinal variations of **E** × **B** vertical plasma drifts in the presunset equatorial topside ionosphere at 1745 LT are examined. Obvious influences of geomagnetic fields on longitudinal variations of **E** × **B** vertical plasma drifts, which also show a seasonal dependence, have been found. During the June solstice, the relative vertical plasma drifts is most significantly influenced by the geomagnetic field declination. However, the relative vertical plasma drifts during the December solstice more strongly correlates with the geomagnetic field strength. Although the relative vertical plasma drifts during equinox are also influenced by the geomagnetic field declination, an underlying dependence on magnetic field magnitude, as seen in December, is also present.

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1. Introduction

[2] At equatorial and low latitudes, many important ionospheric phenomena, such as the equatorial electric jet (EEJ), equatorial ionization anomaly (EIA), and equatorial spread *F*, are all closely related to the ionospheric electric fields and **E** × **B** plasma drifts that are mainly driven by *E* and *F* region dynamos [e.g., *Heelis*, 2004]. Equatorial ionospheric **E** × **B** plasma drifts have been studied extensively with the incoherent scatter radar at Jicamarca [e.g., *Fejer*, 1991], with ionosonde and other spaced receiver techniques [e.g., *Abdu et al.*, 1981], and with satellites [e.g., *Coley and Heelis*, 1989; *Fejer et al.*, 1995]. These measurements suggest that significant longitudinal variations in equatorial plasma drifts exist at different local times and seasons. In particular the equatorial sunset **E** × **B** plasma drifts and associated phenomena also vary dramatically with longitude [e.g., *Abdu et al.*, 1981; *Batista et al.*, 1996; *Sastri*, 1996; *Su et al.*, 1996; *Doumouya et al.*, 2003]. Many factors can contribute to the longitudinal variations of equatorial ionospheric electric fields and **E** × **B** plasma drifts. Variations in thermospheric winds that drive the ionospheric dynamo may cause longitudinal variations. Magnetospheric electric fields, which penetrate from high latitudes to the equator even during magnetically quiet times, vary with universal time and may also cause longitudinal variations of equatorial ionospheric electric fields. Longitudinal variation of the geomagnetic field strength and declination, as well as of the geographic latitude of the magnetic equator, can also be expected to have an influence. *Batista et al.* [1996] and *Hartman and Heelis* [2007] both described the longitudinal variations of equatorial plasma drifts associated with the longitudinal variations of geomagnetic declination. *Deminov et al.* [1988] and *Walker* [1981] also found longitudinal variations of equatorial **E** × **B** plasma drifts that may be related to longitudinal variations of geomagnetic field strength along the equator.

[3] In the past 30 years, great progress has been made in the study of plasma dynamics in the topside ionosphere [e.g., *Heelis et al.*, 1978; *MacPherson et al.*, 1998; *Venkatraman and Heelis*, 2000; *Rich et al.*, 2003; *Liu et al.*, 2007a, 2007b]. Although the equatorial *F* region vertical plasma drifts generally are assumed to be independent of altitude, *Murphy and Heelis* [1986] and *Pingree and Fejer* [1987] both described the relationship between the altitude gradient in the vertical drift and the zonal drift velocity at the dip equator concluding that the vertical drift velocity is dependent on altitude. Thus, we note that longitudinal variations of equatorial vertical drifts in the topside ionosphere may be different from those in the neighborhood of the *F* region peak as indeed is seen in the results from Jicamarca and Arecibo for example [*Fejer et al.*, 1991; *Fejer*, 1993]. The topside ionospheric **E** × **B** plasma drifts and associated phenomena certainly show significant longitude variations that may be related to longitudinal variations in the geomagnetic field [e.g., *West and Heelis.*, 1996; *Hartman and Heelis*, 2007]. Here, we will describe the longitudinal

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variations of the presunset $\mathbf{E} \times \mathbf{B}$ vertical plasma drifts at 1745 LT in the equatorial topside ionosphere using measurements from the Defense Meteorological Satellite Program (DMSP) F13 satellite.

2. Data and Observations

[4] The series of the DMSP spacecraft, which are designated with the letter F and the flight number (e.g., F13) are in sun-synchronous polar orbits. The average altitude of F13 over the geographical equator over its lifetime is ~850 km. The orbital inclination of F13 is 98.8°. The period of an orbit is about 101 min, and consecutive orbits are separated in longitude by 25.5°. Since 1987 each spacecraft has carried a "Special Sensor-Ions, Electrons and Scintillation" (SSIES) package to monitor the behavior of thermal plasma in the topside ionosphere. The nearly constant local time of the DMSP orbital planes at middle and low latitudes makes their ionospheric measurements unique for allowing latitude and longitude variations in the plasma characteristics to be more noticeable. In this work we seek to discover the longitudinal variations of $\mathbf{E} \times \mathbf{B}$ vertical plasma drifts in the presunset topside ionosphere observed at the dip equator by the DMSP spacecraft. The vertical plasma drift is measured with the onboard ion drift meter (IDM). The F13 orbit is approximately dawn-dusk, we choose data in the dusk (the average local time is 1745) sectors observed by this spacecraft from 2000 to 2002 for analysis. The data are provided at the University of Texas, Dallas (UTD) Web site (http://cindispace.utdallas.edu/DMSP/) with 4-s resolution.

[5] *Hartman and Heelis* [2007] had examined longitudinal variations of vertical plasma drift at the dip equator in the topside ionosphere using the data of DMSP F15. They pointed out that there is an absolute uncertainty in DMSP F15's data due to an uncertainty in the pointing of the sensor look direction, examination of the original data indicates that the uncertainty is between 70 m/s and 140 m/s (0.5–1.0°). We found a similar issue in the DMSP F13 data. To solve this problem, as *Hartman and Heelis* [2007] had done, we examined the relative variations by removing a monthly average from the data. The vertical drift measurements are originally sampled at 6 Hz and 4-s averages are assembled to represent the data sample rate of the in-track drift and to provide a latitude resolution of about 0.25°. Only the data whose dip angle between ±2° have been used in this study. We determined the dip angle using the International Geomagnetic Reference Field (IGRF) model for the appropriate epoch. Only the data for which the standard deviation (of the nominally 24 measurements) for this 4-s period, is less than 10 m/s have been used. Observations taken during periods of high magnetic activity marked by the $K_p > 3$ were additionally removed from the data set in order to confine our attention to quiet time variations. Because of a seasonal dependence in the longitudinal variation of $\mathbf{E} \times \mathbf{B}$ vertical plasma drifts, we separate the normalized drift data into three seasons designated equinox (March–April, September–October), June solstice (May–August), and December solstice (November–February). The drifts are then collected every 10° in longitude into 36 longitude bins which are each 30° wide. Finally, in each bin the mean values were calculated.

[6] Relative longitudinal variations of quiet time $\mathbf{E} \times \mathbf{B}$ vertical plasma drifts at 1745 LT for these 3 years 2000–2002 are shown in Figure 1. The yearly averaged values of 10.7-cm flux index from 2000 to 2002 are respectively 180.0, 181.1 and 179.4. Therefore, these data observed by DMSP F13 mainly show the longitudinal variations in high solar activity conditions. The vertical bars indicate the standard deviation of the averages shown. Although there are some slight departures, relative longitudinal variations for the same season in each of these 3 years are very similar. For further study of the relative longitudinal variations, we therefore consider the average quiet time presunset relative $\mathbf{E} \times \mathbf{B}$ vertical plasma drifts for 2000–2002 as shown in Figure 2 (gray star line). For comparison, Figure 3 shows the longitudinal variations in the geomagnetic field declination, the geomagnetic field strength and the geographic latitude at the dip equator. When comparing the vertical plasma drifts for different seasons with these various parameters along the dip equator, we find that the June solstice and equinox relative longitudinal variations are very similar to the longitudinal variation in the geomagnetic field declination, while the December solstice relative longitudinal variation is more similar to the inverted longitudinal variation in the geomagnetic field strength.

[7] Considered alone the correlation coefficients for the June solstice and equinox relative vertical plasma drifts against the geomagnetic field declination are respectively 0.9859 and 0.7843. The correlation coefficient between the December solstice relative vertical plasma drifts and geomagnetic field strength is −0.8968. To examine the effect of these different parameters in more detail, we fit the longitudinal variations of relative vertical plasma drifts to the following equation:

$$V_f(L) = V_0 + GB(L) + FD(L), \tag{1}$$

where B denotes geomagnetic field strength which is in unit of Tesla, D denotes geomagnetic field declination which is in unit of degree, L denotes the longitude, and V_0, G, F are fitting coefficients. The values of least squares fitted coefficients and the correlation coefficient (R) between the fitted results and the relative vertical plasma drifts are listed in Table 1. The solid lines in Figure 2 show the fitted results for different seasons. We see that the geomagnetic field declination completely dominates the longitude variations seen in the June solstice. However, as shown in the fitted results, the effect of geomagnetic field declination is essentially absent during the December solstice and significantly weaker during the equinoxes than during the June solstice. When the geomagnetic field declination effects are reduced, a dependence on the geomagnetic field strength becomes apparent. However, even when the effects of geomagnetic field declination are absent during the December solstice, the ability of geomagnetic field strength to account for the longitude variations is not ideal. The correlation coefficient under these conditions is 0.9. The dependence of the longitude variations on geomagnetic field strength is about the same during the equinoxes and the December solstice, while the dependence on geomagnetic field declination seen during the June solstice decreases by

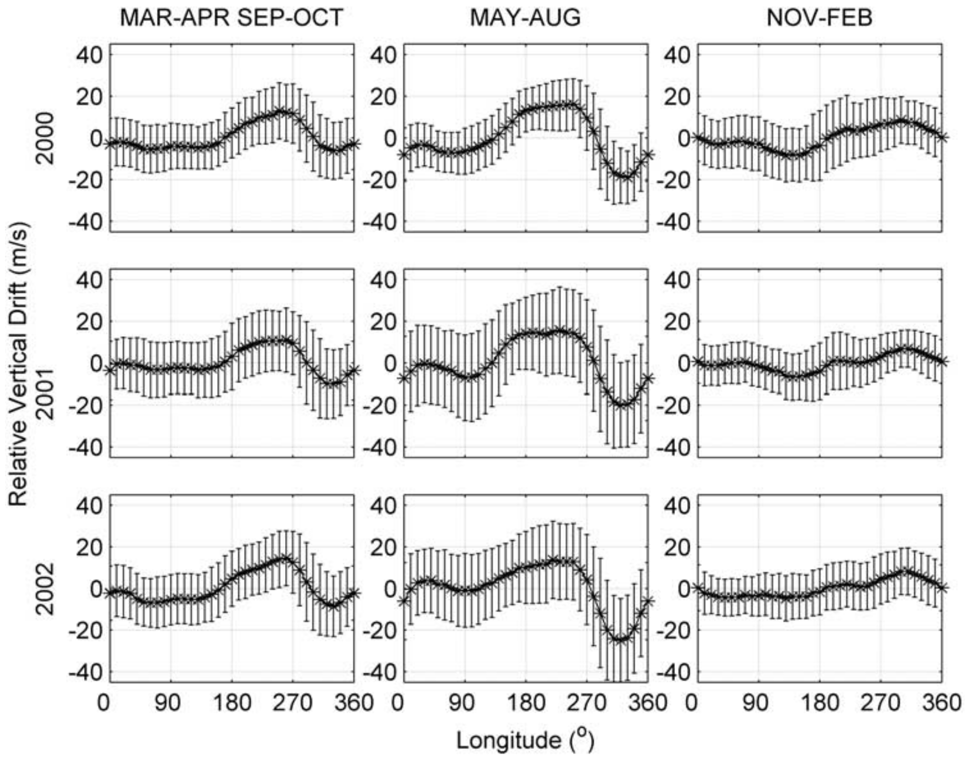

Figure 1. Relative longitudinal variations of quiet time $\mathbf{E} \times \mathbf{B}$ vertical plasma drifts at 1745 LT in different seasons for 2000, 2001, and 2002. See the text for details.

nearly 50% at equinox and is reduced to essentially zero at the December solstice.

3. Discussion and Conclusions

[8] The strong influence of the geomagnetic fields on ionospheric electric fields and $\mathbf{E} \times \mathbf{B}$ plasma drifts has been reported on many occasions [e.g., *Batista et al.*, 1996; *Hartman and Heelis*, 2007]. Popularly, the geomagnetic fields have three consequences modifying the ionospheric electric fields and $\mathbf{E} \times \mathbf{B}$ plasma drifts. First, the ionospheric electric fields couple between both hemispheres along the highly conducting magnetic field lines. This coupling strongly depends on the magnetic field configuration. The field-aligned currents that flow between the northern and southern hemispheres and the hemispherical asymmetry in the flux tube integrated conductivity and dynamo electric fields play important roles in this coupling [e.g., *Hartman and Heelis*, 2007]. Second, the magnetic fields modulate the dynamo electric fields $\mathbf{U} \times \mathbf{B}$ (where $\mathbf{U}$ is neutral wind). Third, the geomagnetic field also modulates the conductivity tensor through its dependence on electron and ion gyrofrequencies.

[9] In the sunset equatorial topside ionosphere, the ionospheric electric fields and $\mathbf{E} \times \mathbf{B}$ plasma drifts are most strongly affected by the F region dynamo [*Crain et al.*, 1993]. The winds contribute to the equatorial vertical plasma drift at the 850 km magnetic apex because of their dynamo action at the foot points of the magnetic field lines in the F region at magnetic latitudes near 15° where both meridional and zonal winds have components perpendicular to the magnetic field. The magnitude of the wind components perpendicular to the magnetic field is strongly dependent on the magnetic declination and thus, as pointed out by *Hartman and Heelis* [2007], the F region wind dynamo appears to be a good candidate to explain variations related to the geomagnetic field declination. Actually, similar to the relative $\mathbf{E} \times \mathbf{B}$ vertical plasma drifts during June solstice observed by DMSP F13, longitudinal variations of equatorial vertical plasma drifts and associated phenomena, which may relate to the longitudinal variation of the geomagnetic declination, are also found by *Abdu et al.* [1981], *Batista et al.* [1996], and *Hartman and Heelis* [2007]. *Hartman and Heelis* [2007] examined longitude variations in the daytime relative vertical ion drift in the topside ionosphere. They invoked a hemispherical asymmetry in the *F* region flux tube integrated conductivity to produce hemispheric differences in the zonal current driven by the component of the neutral wind in the magnetic meridian. This wind component will maximize when the geomagnetic field declination allows geographic meridional and zonal winds to add positively in the magnetic meridian. The hemisphere with the largest flux tube integrated conductivity is that located at the later local time. Then hemispheric differences in the wind driven current will result in vertical drift perturbations that are longitudinally dependent such that downward perturbations are preferentially seen in the June solstice (December solstice) at longitudes where the magnetic declination is positive (negative).

[10] We may invoke a similar argument for our data set. However, we must note that, near dusk, the hemisphere with the larger flux tube integrated conductivity is that located at the earlier local time. We should also note that in this case the F region zonal neutral wind will be directed to the east

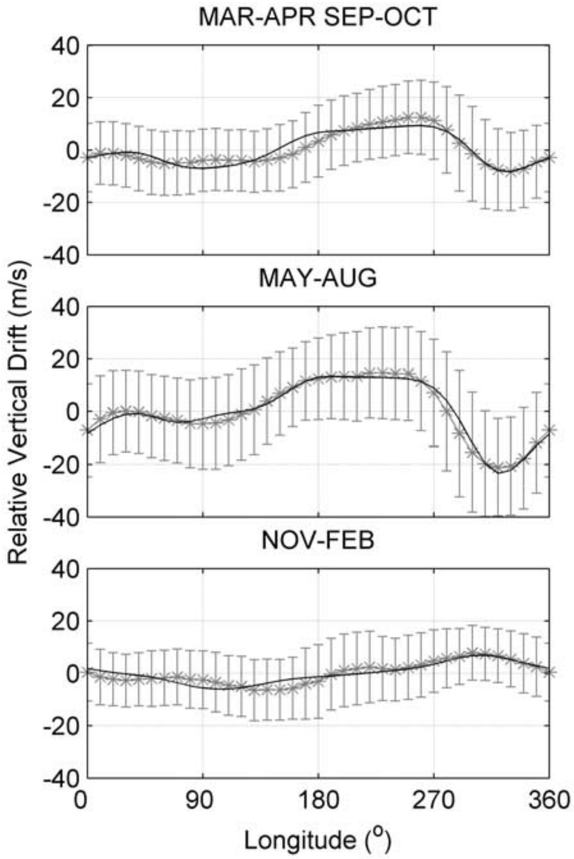

Figure 2. Relative longitudinal variations of averaged quiet time presunset $\mathbf{E} \times \mathbf{B}$ vertical plasma drifts (gray star line) in different seasons from 2000 to 2002. The solid lines show fitting results of vertical plasma drifts using equation (1). See the text for details.

rather than the west. This will change the declination for which geographic meridional winds (summer-to-winter near sunset) and zonal winds positively contribute a component in the magnetic meridian. Because of the different orientation of the magnetic meridian relative to the terminator, large hemispheric differences in the flux tube integrated conductivity are produced at 1745 LT. During June solstice, in the region of positive (negative) magnetic declination, a larger local time gradient in the conductivity can appear at the southern (northern) foot point than at the northern (southern) foot point. The hemispheric differences of geomagnetic field configuration will also produce hemispheric differences in the zonal wind driven current, which relate to the component of the neutral wind in the magnetic meridian. As this wind component will maximize when the geomagnetic field declination allows geographic meridional and zonal winds to add positively in the magnetic meridian, the zonal wind driven current will also maximize in this condition. With the coupling between southern and northern hemispheres, the ionospheric electric fields and $\mathbf{E} \times \mathbf{B}$ plasma drifts in the region of positive (negative) magnetic declination will be mainly controlled by the F region dynamo at the southern (northern) foot. Then, eastward (westward) polarization fields will be produced, and result in a relative upward (downward) drifts perturbation at this location [see also *Hartman and Heelis*, 2007]. Because of the different orientation of the magnetic meridian relative to the terminator, the magnetic declination's effect on the vertical drifts during December solstices are opposite to that during June solstices. Thus, the expected vertical drift perturbations would again be downward and appear in the June solstice (December solstice) when the magnetic declination is negative (positive).

[11] In addition to this longitudinally-dependent dynamo process near dusk, we must also consider the plasma drifts that constitute a so-called prereversal enhancement (PRE) [*Woodman*, 1970]. The PRE, which is mainly produced by the *F* layer dynamo [*Crain et al.*, 1993], develops under the combined action of an eastward thermospheric wind and the longitudinal gradient in the field line integrated Pedersen conductivity that exists across the sunset terminator [*Rishbeth*, 1971]. So there is a well established longitudinal dependence in these upward drifts perturbations that favors the longitude for which the terminator and the magnetic meridian are coaligned [*Abdu et al.*, 1981; *Tsunoda*, 1985]. At sunset, the integrated Pedersen conductivity gradient has a major contribution from conjugate E layers, and therefore generally attains its largest values when the sunset terminator moves parallel to (aligned with) the magnetic meridian,

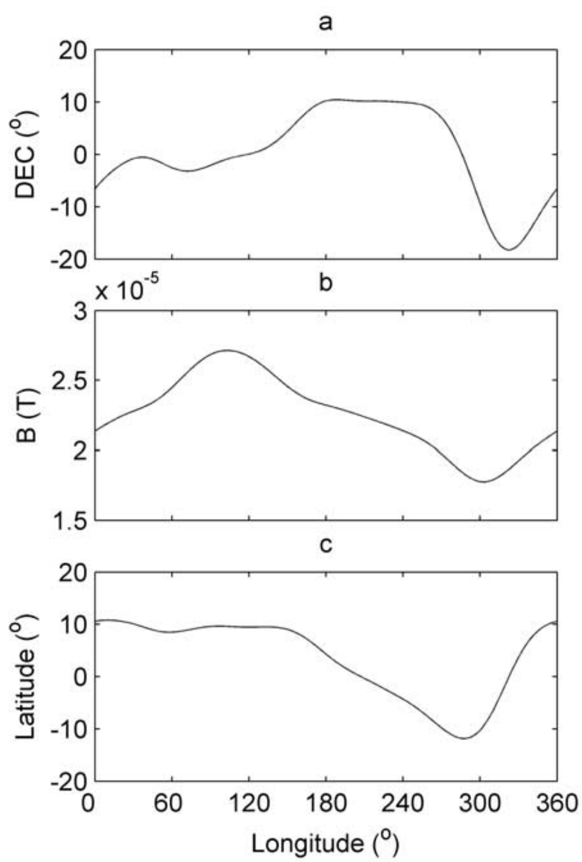

Figure 3. Longitudinal variations of various parameters at the dip equator at the height of 850 km. Parameters are (a) geomagnetic field declination (DEC), (b) geomagnetic field strength, and (c) geographical latitude.

Table 1. Fitting Coefficients and Correlation Coefficient in Equation (1) for Different Seasons

Season	V_0	G	F	R
Equinox	29.2518	-1.2919×10^6	0.7296	0.9433
June	0.1007	-0.0071×10^6	1.2866	0.9861
December	30.0116	-1.3301×10^6	-0.0467	0.9013

which corresponds to near-simultaneous sunset at conjugate *E* layers. And, the largest integrated Pedersen conductivity gradient leads to the generation of PRE with largest intensity. In this case upward drift perturbations are preferentially expected for the June solstice (December solstice) in regions of positive (negative) declination.

[12] Since the vertical plasma drifts during the period of PRE change rapidly, these upward drift perturbations at 1745 LT should also be modified by the local time of PRE peaks. An earlier local time of PRE peaks will increase the upward drift perturbations at 1745 LT. As the local time of PRE peaks may depend on the local time of sunset at conjugate E layers, both the location of the dip equator with respect to the geographic equator and the geomagnetic declination can modify the local time of PRE peaks. Actually, the seasonal and longitudinal variation of the local time of PRE peaks have been shown in a series of work and empirical model [e.g., *Fejer*, 1991; *Batista et al.*, 1996; *Scherliess and Fejer*, 1999; *Fejer et al.*, 2008]. Since the equatorial vertical drifts vary with altitude, the local time of PRE peaks may also depend on altitude. Because of the lack of enough observations which cover the periods of PRE at the altitude of 850 km, detailed simulations are needed to study the seasonal and longitudinal variations of the effect of PRE.

[13] In the December solstice, the above mechanisms should also affect the ionospheric vertical drifts and are consistent with the longitudinal behavior observed in a series of work. For example, with the vertical plasma drifts data taken by ROCSAT-1 at the 600 km, *Fejer et al.* [2008] and *Su et al.* [2008] both found that the longitudinal distributions of quiet time equatorial PRE peaks in the December solstice maximize exactly at the same longitude region as that of the maximum westward declination angle (near 320°), which may imply the effect of above mechanisms. Although these mechanisms are also generally consistent with the longitudinal behavior we observe in the topside ionosphere, they do not account for the strong seasonal asymmetry that appears to favor a dependence on geomagnetic field strength in the December solstice at the height of DMSP. Large longitudinal variations of equatorial vertical plasma drifts and associated phenomena, which may be caused by the longitudinal variation of geomagnetic field strength, are found both by *Deminov et al.* [1988] and *Walker* [1981]. Through a simulation, *Vichare and Richmond* [2005] studied the longitudinal variation of evening vertical ionospheric drifts at the magnetic equator and found a similar result to that of *Walker* [1981]. Our work also shows that the December solstice relative $\mathbf{E} \times \mathbf{B}$ vertical plasma drifts at 1745 LT decrease with increasing geomagnetic field strength. For a given electric fields, $\mathbf{E} \times \mathbf{B}$ plasma drifts ($\mathbf{E} \times \mathbf{B}/B^2$) will decrease with increasing geomagnetic field strength. However, as the dynamo electric fields ($\mathbf{U} \times \mathbf{B}$) and dynamo currents will increase with increasing geomagnetic field strength, the connection between the $\mathbf{E} \times \mathbf{B}$ plasma drifts and the geomagnetic field strength is not straightforward [see also *Richmond et al.*, 1980; *Abdu et al.*, 2005]. As per the discussions in above paragraphs, the development of PRE should partly depend on integrated Pedersen conductivity gradient [*Rishbeth*, 1971], which has a major contribution from conjugate E layers. Energetic particle precipitation over the South Atlantic Magnetic Anomaly (SAMA) region is a well-established phenomenon. The ionospheric effects of enhanced ionization in the E and D region of the ionosphere over the SAMA region, which are caused by energetic particles, are also well established. The enhanced ionization will also enhance integrated Pedersen conductivity and its gradient. Thus, *Abdu et al.* [2005] associated enhanced sunset $\mathbf{E} \times \mathbf{B}$ plasma drifts and related phenomena over the SAMA region with enhanced ionization and conductivity gradients at *E* layer heights due to energetic particle precipitation in the ionosphere over the SAMA region. The extra ionization which is operative even under "quiet" conditions could produce enhanced conductivity local time gradient at sunset resulting in enhanced $\mathbf{E} \times \mathbf{B}$ vertical plasma drift near sunset within and around the SAMA longitude sector [see *Abdu et al.*, 2005]. As the SAMA region is in the southern hemisphere, the largest impact of these conductivity variations will be seen in the December solstice when the northern flux tube integrated conductivity is a minimum. Thus, vertical drift in the equatorial topside ionosphere near sunset will be most strongly correlated with the geomagnetic field strength during the December solstice. However, since the enhanced ionization at *E* layer heights over the SAMA region should vary with the magnetic latitude, the influence of this mechanism on the vertical plasma drifts should vary with altitude. And this effect during the December solstice may also be modified by the location of the dip equator with respect to the geographic equator. Detailed simulations are needed to separate effects that appear simultaneously in the observations.

[14] Using the DMSP F13 satellite equatorial vertical plasma drift data acquired from 2000 to 2002, we have studied the relative longitudinal variations of vertical plasma drifts in the presunset equatorial topside ionosphere. The December solstice relative $\mathbf{E} \times \mathbf{B}$ vertical plasma drifts are most strongly correlated with the geomagnetic field strength while the June solstice relative $\mathbf{E} \times \mathbf{B}$ vertical plasma drifts are more linearly related to the geomagnetic field declination. At equinox the dependence on magnetic declination is significantly reduced from that seen in the June solstice and the dependence on the magnetic field intensity seen in the December solstice appears identically.

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