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Quiet time equatorial F region vertical plasma drift model derived from ROCSAT-1 observations

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[1] We have used five years of measurements on board the ROCSAT-1 satellite to develop a detailed quiet time global empirical model for equatorial F region vertical plasma drifts. This model describes the local time, seasonal and longitudinal dependence of the vertical drifts for an altitude of 600 km under moderate and high solar flux conditions. The model results are in excellent agreement with measurements from the Jicamarca radar and also from other ground-based and in situ probes. We show that the longitudinal dependence of the daytime and nighttime vertical drifts is much stronger than reported earlier, especially during December and June solstice. The late night downward drift velocities are larger in the eastern than in the western hemisphere at all seasons, the morning and afternoon December solstice drifts have significantly different longitudinal dependence, and the daytime upward drifts have strong wave number-four signatures during equinox and June solstice. The largest evening upward drifts occur during equinox and December solstice near the American sector. The longitudinal variations of the evening prereversal velocity peaks during December and June solstice are anti-correlated, which further indicates the importance of conductivity effects on the electrodynamic of the equatorial ionosphere.

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1. Introduction

[2] Low latitude ionospheric plasma drifts and electric fields are controlled by complex E and F region electrodynamic processes, which are known to vary significantly with local time, season, solar cycle, geomagnetic activity and longitude [e.g., Fejer, 1997]. The understanding of this large variability during quiet and disturbed times is fundamental for improved forecasting of the low latitude ionospheric weather.

[3] Equatorial F region vertical plasma drifts have been measured extensively using coherent and incoherent scatter radar measurements at the Jicamarca Radio Observatory (11.95°S, 76.87°W; magnetic dip 2°N), and they have also been inferred from daytime magnetometer [e.g., Anderson *et al.*, 2004] and nighttime ionosonde observations [e.g., Abdu *et al.*, 1981]. These measurements have been used in numerous case studies of the quiet and disturbed equatorial ionosphere, and also for the development of regional empirical plasma drift models [e.g., Abdu *et al.*, 1995; Sastri, 1996; Batista *et al.*, 1996; Fejer, 1997; Fejer *et al.*, 1999; Scherliess and Fejer, 1999].

[4] Low latitude vertical plasma drifts measurements were made by the Ion Drift Meter (IDM) probe on the board the low inclination (19.96°) Atmosphere Explorer-2 (AE-E) satellite from January 1977 through December 1979. During this period, the AE-E satellite was in nearly circular orbits at altitudes from 260 to 450 km. Coley *et al.* [1990] showed that the local time dependence of the longitudinally averaged AE-E equatorial vertical plasma drifts during equinox and December solstice high solar flux conditions was similar to that derived from Jicamarca radar measurements. They also highlighted the occurrence of large longitudinal variations during June solstice. Equatorial vertical plasma drifts measurements by the high inclination (90°) Dynamics Explorer-B (DE-2) between August 1981 and February 1983 [Coley and Heelis, 1989], and zonal electric field observations by the equatorial San Marco satellite during April–August 1988 [Maynard *et al.* [1995] were also in good agreement with the Jicamarca drifts. The equatorial vertical drift databases from the DE-2 and San Marco satellites are too small for detailed studies of longitudinal effects.

[5] Fejer *et al.* [1995] presented the first comprehensive study of season, solar cycle and longitude effects on quiet time equatorial F region vertical ion drifts using IDM data from the AE-E satellite. They showed that the equatorial drifts have large day-to-day and seasonal variations, and that solar cycle effects are most pronounced near dusk, where they increase strongly from solar minimum to solar maximum. This study also presented empirical models for the vertical drifts at four longitudinal sectors representative

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of the Africa-Indian (0° – 150° E), Pacific (150° – 210° E), Western American (210° – 300° E), and Brazilian (300° – 360° E) equatorial regions. *Scherliess and Fejer* [1999] used incoherent scatter radar observations from Jicamarca and IDM data from AE-E to develop the first global empirical model for quiet equatorial F region vertical plasma drifts. This analytical model, which uses products of cubic-B splines to describe the temporal and spatial variations of the equatorial vertical drifts, has extensively been used for modeling equatorial ionospheric processes.

[6] Recent satellite studies have reported wave number-four longitudinal signatures on the strengths of the nighttime equatorial ionization anomaly [*Immel et al.*, 2006], and of the noontime equatorial electrojet [*England et al.*, 2006], which were attributed to the longitudinal modulation of equatorial zonal electric fields. They suggested that this modulation is due to electrodynamic effects of a non-migrating E region tide driven by fixed sources of tropospheric heat [*Hagan and Forbes*, 2002; *Forbes et al.*, 2003]. *Hartman and Heelis* [2007] presented morning ion drift measurements made on board the Defense Meteorological Satellite Program (DMSP) in the topside equatorial ionosphere, which show that wave number-four longitudinal variations occur throughout the year, but have most clear signatures during equinox. *Kil et al.* [2007] reported wave number-four longitudinal patterns on seasonally averaged equatorial vertical plasma drift velocities and plasma densities measured by the first Republic of China Satellite (ROCSAT-1) at an altitude of about 600 km. They also showed that the seasonally averaged evening vertical drifts do not exhibit the wave number-four longitudinal structure. More recently, *Scherliess et al.* [2008] have used a very extensive database of total electron content (TEC) from the TOPEX satellite to study the evolution of wave number-four longitudinal effects on the low latitude ionospheric plasma density. These events were most clearly defined during equinox and June solstice.

[7] Three-dimensional global coupled ionosphere-thermosphere models have increasingly been used to study the electrodynamics of the equatorial region. *Fesen et al.* [2000] successfully simulated the seasonal and local time variations of the equatorial F region vertical and zonal plasma drifts using the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM). This study showed that the E region semidiurnal tide plays an important role on the daytime drifts. *Millward et al.* [2001] examined the global effects of tidal forcing on F region equatorial vertical ion drifts using the Coupled Thermosphere-Ionosphere-Plasmasphere model (CTIP). They showed that the prereversal enhancement of the evening vertical ion drifts is not affected by tidal forcing during periods of high solar activity. Recently, *Vichare and Richmond* [2005] used simulations from the Magnetosphere-Thermosphere-Ionosphere-Electrodynamics General Circulation Model (MTIEGCM) and experimental observations to study the effects of various ionospheric and thermospheric parameters on the longitudinal variation of the evening equatorial vertical plasma drifts during equinox. These simulations indicate that the evening upward drifts are larger in the American-Atlantic sector than in the Indian sector, which could possibly be due to the longitudinal variation of the strength of the geomagnetic field.

[8] In this work we present the first detailed study of the local time, longitudinal, seasonal, and solar cycle dependence of the equatorial F region vertical plasma drifts measured by the Ionospheric Plasma and Electrodynamics Probe Instrument (IPEI) aboard ROCSAT-1. This satellite was launched on 27 January 1999 into a circular orbit at an altitude of 600 km with an orbital inclination of 35° and a period of 97 min. This mission, which ended early July 2005, covered 24 h local times in 25 days. The IPEI measurements, made continuously from mid March 1999 to early June 2004, have been used in numerous case studies of the low latitude ionosphere [e.g., *Lin et al.*, 2001; *Su et al.*, 2002, 2003; *Chao et al.*, 2003; *Kil et al.*, 2007]. In the following sections we initially describe in detail our data selection and model development. Then, examine the general characteristics of these equatorial vertical drifts, and compare our results with those from previous studies.

2. Measurements and Data Selection

[9] The characteristics of the IPEI were described by *Yeh et al.* [1999]. In this probe, the cross track ion velocity components were determined from the arrival angles of the ions with 1° corresponding to about 125 m/s. The error on these drift measurements were typically smaller than 10% when the ion density was larger than 10^3 cm^{-3} and the percentage of oxygen ions exceeded 85%, but, as we will see later, they were much larger during late night low solar flux periods, due to the larger percentage of light ions at about 600 km. The vertical velocity is usually a combination of the ion drift components perpendicular and parallel to the geomagnetic field, but near the dip equator it corresponds basically to the electrodynamic drift driven by the zonal electric field.

[10] We have examined the entire ROCSAT-1 database of 15-s averaged quiet time ($K_p \leq 3$) drift measurements which span from mid March 1999 through early June 2004. We have discarded data from March–June 1999, which have very large variability, and from the end of February to mid March 2000 because of an anomalous offset. We have also deleted measurements within a few seconds from noon throughout the entire database, which were also clearly erroneous.

[11] We selected and analyzed the ROCSAT-1 equatorial drifts using basically the methodology described by *Fejer et al.* [1995]. However, since this satellite was at a much higher altitude than AE-E, particularly during lower solar flux conditions, additional data analysis constraints were also necessary. We have first determined that the average drift patterns using observations within 5° and 2.5° of the dip equator were largely identical. Therefore the results to be presented below were obtained using measurements within 5° of the dip equator, since they have higher statistical significance.

[12] The accuracy of the drifts measurements decreases markedly with decreasing ion density and increasing density of light ions. Since we have not used the ion composition data, we have tried to minimize the measurement errors by first examining the average drifts corresponding to plasma densities larger than 10^4 cm^{-3} , $2 \times 10^4 \text{ cm}^{-3}$, $5 \times 10^4 \text{ cm}^{-3}$, and 10^5 cm^{-3} . Figure 1 shows an example of a scatterplot of the drift measurements

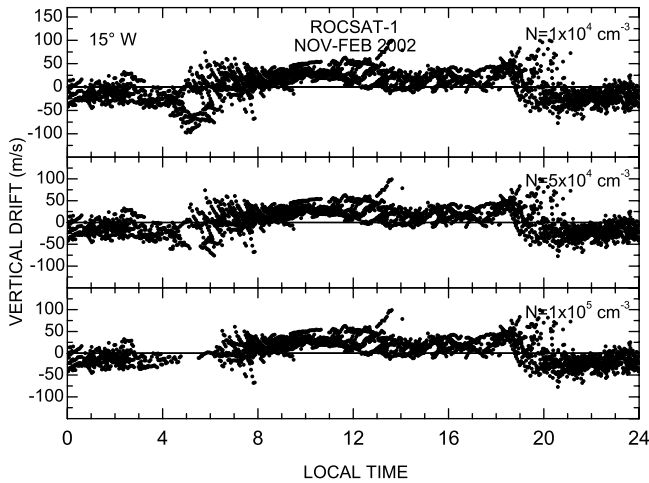


Figure 1. Examples of scatterplots of quiet time equatorial vertical drift velocities over a 30° longitudinal sector measured by ROCSAT-1 for three plasma density thresholds.

obtained using three plasma density thresholds. This Figure indicate that the use of larger threshold plasma densities decreases the scatter and the number of late night measurements. The upward drifts after about 1900 LT are due to equatorial plasma depletions, which are most frequent in the Atlantic-American sector. The lower plasma densities in the late night sector are generally associated with larger downward velocities and also with larger scatter and errors in the measurements, especially during low solar flux conditions. Our analysis indicated the occurrence of unrealistically large late night downward velocities for plasma densities smaller than about 10^4 cm^{-3} due to the higher percentage of light ions. As will be shown later, this resulted in large departures from the curl-free condition for the longitudinally averaged zonal electric fields.

[13] We obtained our best overall results using drifts corresponding to plasma densities larger than 10^5 cm^{-3} between 0800 and 0200 LT, and larger than $5 \times 10^4 \text{ cm}^{-3}$ from 0200 to 0800 LT, which maximized both the accuracy of the measurements during the day and the number of late night observations. We note that the number and accuracy of our late night measurements decreased with solar flux, especially during June solstice due to the higher percentages of light ions. Finally, we tried to minimize the effects of upward drifts associated with plasma depletions, and excluded velocities with magnitudes larger than 100 m/s since, under geomagnetically quiet conditions ($K_p \leq 3$), they generally appear to be due to instrumental effects or, during early night periods, to equatorial plasma depletions. We will show later than these constraints seem to give quite accurate average drifts, except for relatively low solar flux ($S_a < 130$) late night June solstice conditions.

3. Model Development and Accuracy

[14] Our database consists of over 560,000 quiet time ($K_p \leq 3$) measurements. These data were grouped into four month seasonal bins representing December solstice (November–February), June solstice (May–August), and equinox (March–April, September–October) and 15° over-

lapping 30° wide longitudinal bins. We have used 1-h local time bins, except in the 1700–2200 LT sector, where we used 30 min bins shifted every 15 min, in order to more accurately account for rapidly changing evening prereversal drift enhancements. When averaging the data, we discarded points outside two standard deviations.

[15] We have determined that the variations of the drift velocities with solar flux were best reproduced by using bilinear relationships. This was also the case for the vertical drifts measured by the Jicamarca radar [Scherliess, 1997]. For each local time, season, and longitude bin, we have first grouped the drift data into three overlapping solar flux index bins: $S_a \leq 130$, $S_a \leq 160$, and $S_a > 160$. The average solar flux indices in these bins were about 110, 130, and 185, respectively, with largest values during equinox and smallest during June solstice. Other solar flux groupings were also tried, but they resulted in inferior fits to the data. We have determined the variations of the drifts with solar flux for $100 \leq S_a \leq 120$ and $140 \leq S_a < 210$ using our binned data and the assumption of a linear drift dependence with solar flux. Between 0000–1700 and 2200–2400 LT sectors, we used 4 h local time bins shifted every 2 h. It is possible that these large bins have smoothed out too much the early morning flux dependence, but this was necessary since the data are sparse in this period. For the 1700–2200 LT sector, where the drift velocities often change rapidly, we have calculated the solar dependence using 60 min local time bins shifted by 30 min, except for a few cases that required the use of 30 min bins shifted by 15 min. The derived flux variations for $S_a \leq 120$, and $S_a \geq 140$ are generally quite similar. For $120 < S_a < 140$, we have interpolated between our low and high flux variations. Finally, we have performed 3 point running averages on the longitudinal variations of the derived flux dependence. The solar flux variations derived from our data are generally consistent with those presented by Scherliess and Fejer [1999], except near dusk where we have stronger solar flux dependence.

[16] The empirical model derived using the procedure outlined above gives the quiet time ($K_p \leq 3$) equatorial vertical drifts at an altitude of 600 km for each season usually in 30 min local time, 15° overlapping 30° wide longitudinal bins for $S_a = 100$ –200. In the 1700–2200 LT sector, the drifts are specified in 15 min local time bins. As discussed below, and further highlighted later, these model drifts are most accurate for equinox and December solstice.

[17] The equatorial zonal ionosphere electric fields, which drive F region vertical drifts, must be irrotational on the times scales and for the quiet time conditions considered here, so that their line integrals along the dip equator must be zero; i.e.,

$$\oint E \, d\ell = \oint B v_z \, d\ell = 0 \quad (1)$$

where B denotes the equatorial magnetic field strength (between 0.19 and 0.30 G at the height of the satellite), and v_z is the vertical drift velocity. Scherliess and Fejer [1999] used this curl-free constraint in the development of their equatorial vertical drift model. We used this condition to estimate the longitudinally averaged accuracy of our empirical models as a function of universal time (UT). We have calculated the values of the above integrals by

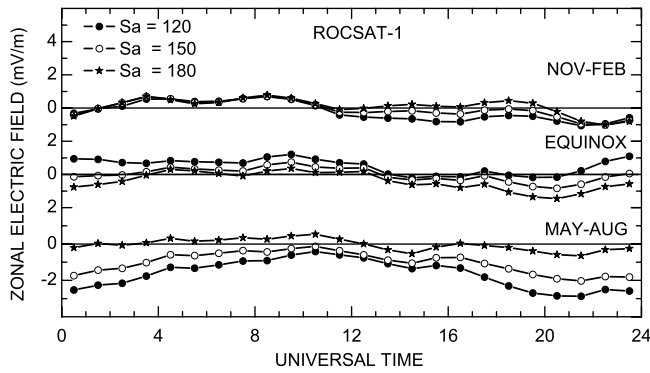


Figure 2. Longitude integrated equatorial zonal electric fields.

summing the products of the average drift velocities and corresponding magnetic field strengths at the dip equator, in hourly and half-hourly 7.5° and 15° longitudinal bins. The magnetic field values for an altitude of 600 km along the dip equator were obtained from the International Geomagnetic Reference Ionosphere (IGRF).

[18] Figure 2 shows the hourly values of the zonal electric fields integrated along the magnetic equator for three solar flux values. In this case, we obtained used a 15° longitudinal grid; nearly identical results were obtained using our higher time and spatial resolution data. Figure 2 indicates that for equinox and December solstice, our vertical drifts

correspond to nearly curl-free electric fields. For June solstice this is the case for high solar flux conditions, but not for lower solar fluxes values when there are increasing departures from the curl-free condition, which are probably due to the larger errors of the late night measurements. We note that for a given UT, a shift in the drift velocities around the globe by 1.5 m/s changes the longitudinally averaged zonal electric field by about 2 mV/m. Since we do not know the exact local time and solar flux dependent accuracy of the drift measurements, we did not attempt to correct them to satisfy the curl-free condition.

4. Results and Discussion

[19] In this section, we initially describe the seasonal and longitudinal variations of the equatorial vertical drifts for the average solar flux conditions ($S_a = 150$) during the ROCSAT-1 mission, which correspond to our most accurate results. Then, we examine their dependence on solar flux. Finally, we compare our results with those from earlier studies.

4.1. General Characteristics

[20] Figure 3 shows the average F region vertical drifts in 8 longitudinal sectors for moderately high solar flux conditions derived from our ROCSAT-1 data. These drifts are upward during the day and downward at night with magnitudes up to about 40 m/s, but which vary significantly with local time and longitude, particularly during the solstices.

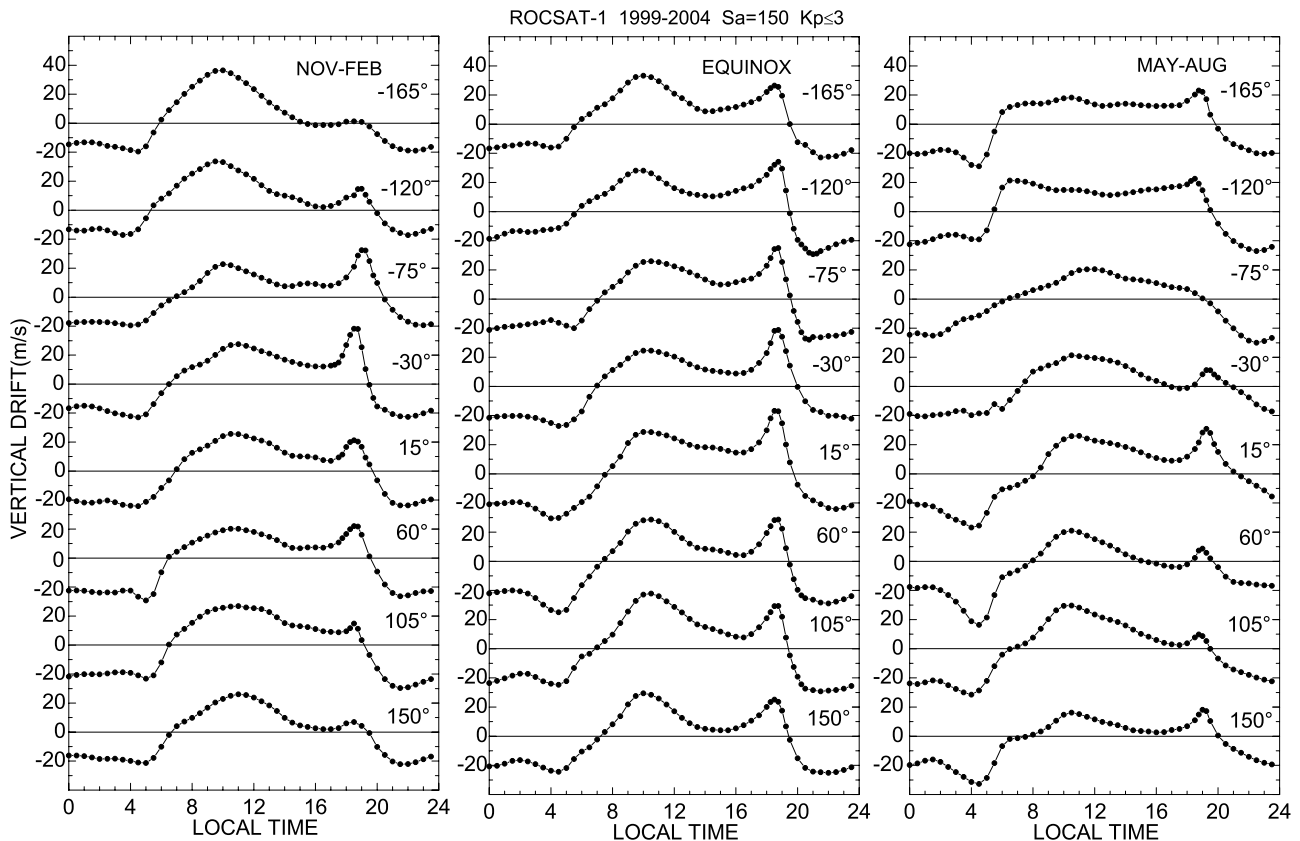


Figure 3. Local time and longitude dependence of quiet time equatorial vertical drifts (positive upward) in eight longitudinal sectors for moderate solar flux conditions.

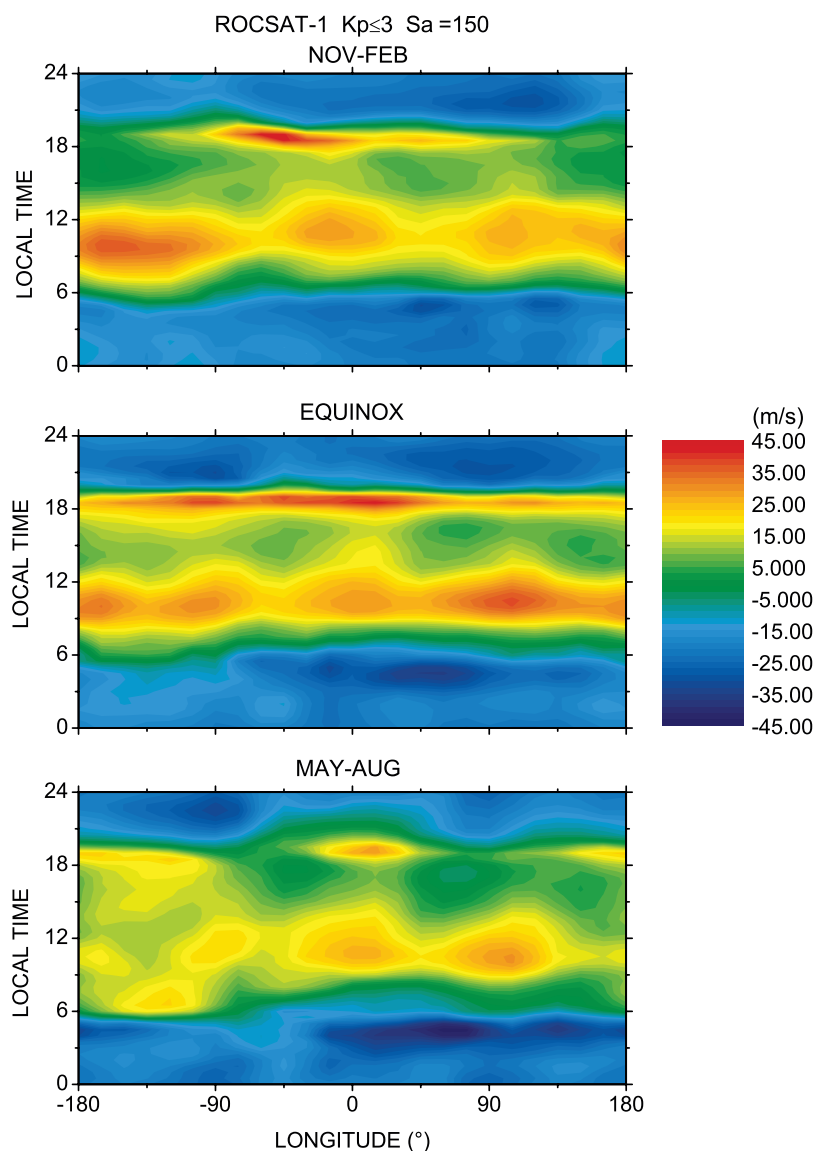


Figure 4. Local time, seasonal and longitudinal dependent equatorial quiet time vertical drift velocities for moderate solar flux conditions.

Large prereversal velocity enhancements (up to about 50 m/s) occur over a broad range of longitudes near dusk during equinox and close to dawn during June solstice. The evening drift reversal times do not change much with longitude during equinox, but vary considerably in the American-African sector during December and June solstice. There are also large variations between the western and eastern hemisphere morning drifts and reversal times during June solstice.

[21] The local time, seasonal and longitudinal dependence of the vertical drifts are illustrated in more detail in Figure 4. The midnight-dawn downward drifts are larger in the eastern than in the western hemisphere, and have largest magnitudes near sunrise during June solstice. Figure 4 also show the large longitudinal variations in the morning and afternoon daytime upward drifts at all seasons. The December solstice data show daytime velocity peaks near 10°W and 100°E at about 1100 LT, and a broad longitudinal sector of enhanced upward drifts between about 170°E and 90°W, centered at

about 1000 LT. During equinox, there are four upward velocity peaks near 170°W, 100°W, 0°E, and 100°E at about 1000 LT. In this season, the daytime longitudinal drift velocity fluctuations appear to generally extend, with decreasing amplitudes, into the evening sector. The June solstice drifts have moderate to large drift peaks near 90°W, 0°E, and 100°E, a considerably smaller peak near 170°W all at about 1100 LT, and also an early morning region of enhanced upward drifts near 140°W. The latter is mostly due to the sudden drift reversal near sunrise (see Figure 3). Figure 4 also illustrate the strong seasonal and longitudinal dependence of the prereversal velocity enhancements and of the evening reversal times. The premidnight downward drifts do not show a clear longitudinal pattern.

[22] Figure 5 presents in the bottom and top panels the seasonal and longitudinal dependence of the upward drift velocities averaged between 0900–1200 LT and 1300–1600 LT, respectively. The equinox, June solstice and the eastern hemisphere December solstice morning and after-

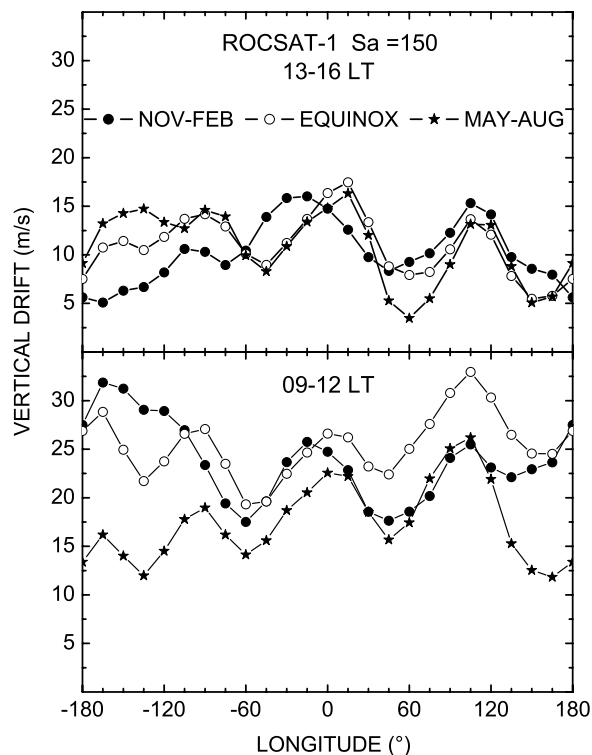


Figure 5. Longitudinal variations of morning and afternoon averaged quiet time vertical drifts.

noon velocity peaks are nearly identical longitudes. On the other hand, the December solstice western hemisphere morning and afternoon drifts have very different magnitudes and longitudinal dependence. In this case, wave number-four signature is not as clear as during the other seasons, as shown also in Figure 4. The morning upward velocities are larger than the afternoon drifts by about 10–15 m/s values, except in the western hemisphere during June solstice. The dayside velocity peaks near 100°E exhibit the smallest local time and seasonal variations, which might be related to the

strong geomagnetic field in this region (H. Lüher, private communication, 2007).

[23] Figures 3 and 4 show large seasonal and longitudinal variations in the evening prereversal velocity enhancements. These are illustrated further in Figure 6. The equinoctial peak velocity enhancements vary between 25 and 45 m/s, with largest values from 120°W to 30°E. The December solstice drifts have smallest magnitudes near 180°E, and largest values in the American sector, where they occur at increasingly later local times toward the west, as shown in Figure 4. The June solstice evening velocity peaks have largest values near 15°E and 180°E, and smallest near 75°E and 60°W. The longitudinal variations of the December and June solstice prereversal velocity enhancements are nearly anti-correlated. This is probably due to magnetic field line integrated conductivity effects, which play a fundamental role on the magnitude of the evening prereversal velocity enhancements. It is interesting to note that, except near 60°W, the evening equinoctial peak drifts correspond approximately to the sum of the solstitial drifts.

4.2. Solar Cycle Effects

[24] Figure 7 shows the longitudinal dependence of the vertical model drifts for $S_a = 130$ and $S_a = 200$. The morning drifts do not change much with solar activity during December solstice and equinox, but the afternoon and evening upward and the nighttime downward drifts increase with solar flux. The solar flux dependence of the December solstice evening drifts varies strongly with longitude. The western hemisphere June solstice drifts show small solar flux effects in the nighttime and early morning sectors and increased upward drifts with solar flux in the noon-evening sector. On the other hand, the eastern hemisphere June solstice data show larger daytime upward and smaller nighttime downward drifts with increased solar activity. We note that the violation of the curl-freeness during moderate and low solar flux June solstice conditions shown in Figure 2, results from the simultaneous decrease in the upward daytime drifts and increase in the postmidnight downward drifts with decreasing solar flux, which is

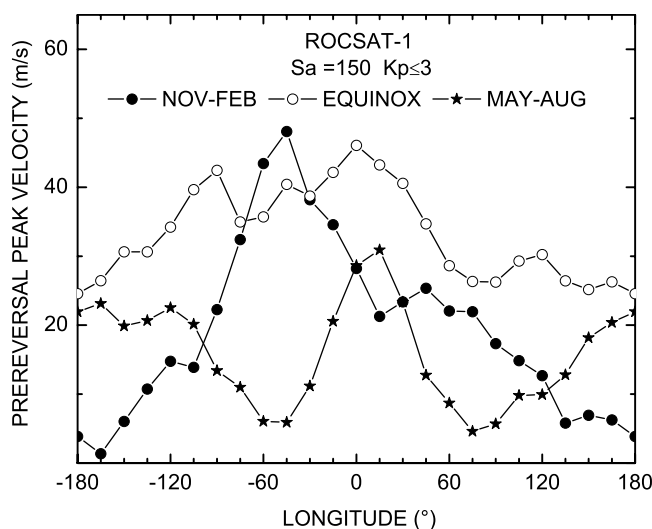


Figure 6. Seasonal and longitude dependence of quiet time evening prereversal velocity peaks.

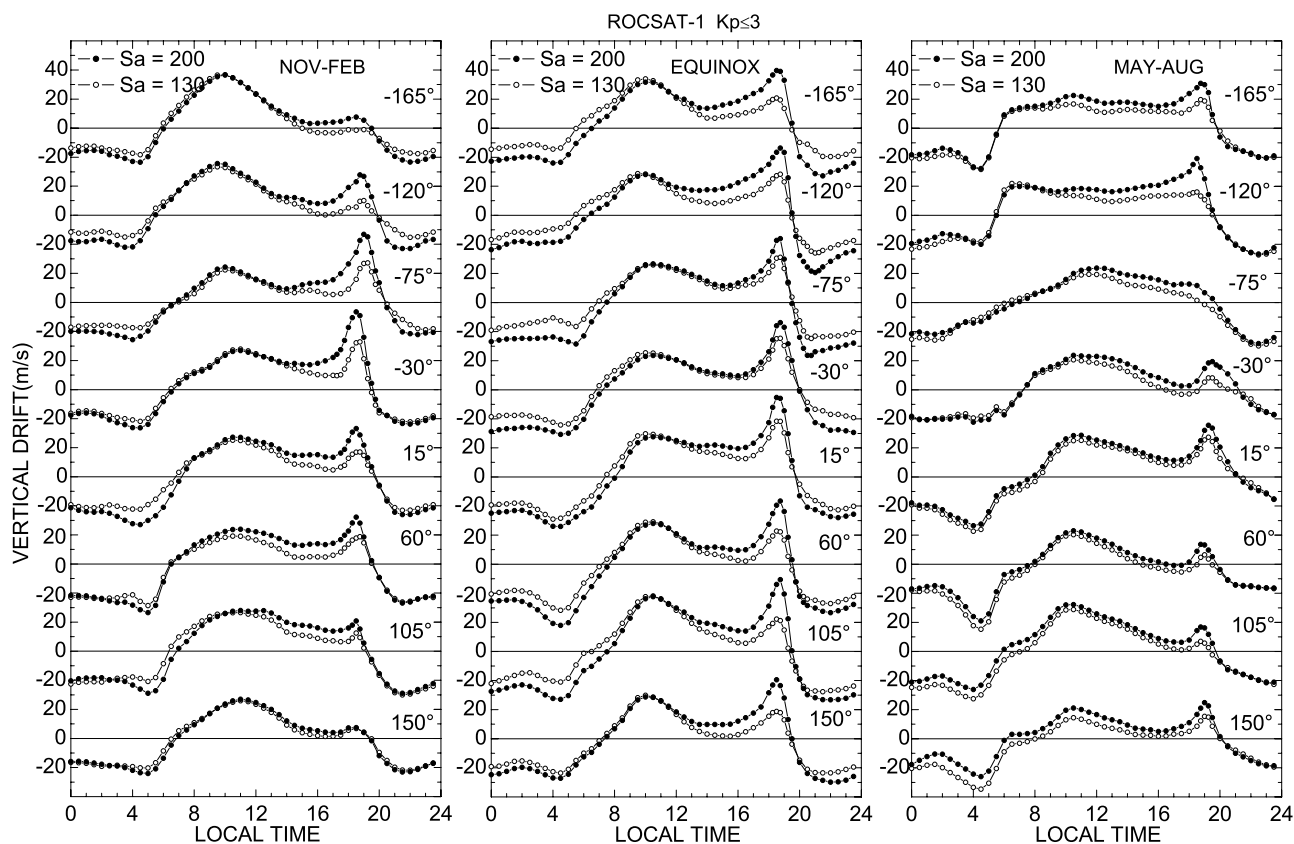


Figure 7. Seasonal and longitude dependence of quiet time equatorial model drift velocities for two decimetric solar flux values.

most pronounced in the eastern hemisphere. Therefore we believe that the solar flux dependence indicated by the eastern hemisphere June solstice drifts in the midnight-early afternoon sector eastern is not realistic. As pointed out earlier, a change in the baselines of these drifts by a few m/s would bring them in closer agreement with both the curl-free condition and expected solar flux dependence.

[25] Figure 7 also indicates that the increase of the evening prereversal velocity enhancements with solar flux varies noticeably with longitude during December and June solstice. The evening reversal times do not change with solar flux, except in the American sector during June solstice. The morning reversal times generally occur earlier with decreasing solar flux during December solstice and equinox, but later in the eastern hemisphere during June solstice, which is related to the solar flux dependence of these drifts and, therefore, might not be realistic.

[26] Figure 8 presents the seasonal and longitudinal variation of the evening prereversal velocity peaks for two solar flux values. This figure shows that the magnitudes of these drifts and their increase with solar flux are longitude dependent. The largest prereversal drift peaks occur during equinox, except near 45° W, where they are largest during December solstice. The longitudinal variation of the evening upward drift peaks is smallest during equinox solar maximum conditions, which suggests that the F region dynamo plays an even more dominant role on the generation of high solar flux evening drifts at all longitudes. On the other hand, the longitudinal variation of the evening

prereversal velocity peaks is largest during December solstice. Figure 8 also shows that the longitudinal variations of the December and June solstice evening peak drifts are largely anti-correlated during both high and low solar flux periods.

4.3. Comparison With Earlier Results

[27] The seasonal and solar dependence of the F region vertical plasma drifts over Jicamarca were discussed in several studies [e.g., Fejer *et al.*, 1991; Scherliess, 1997]. These radar drifts correspond to averages generally between about 300 and 400 km during most of the day, but they correspond to higher altitudes during December solstice and equinox evening periods, and to lower heights in the postmidnight sector at all seasons, as a result of the solar flux dependent evening upward and nighttime downward motions of the equatorial F layer, respectively. On the other hand, our ROCSAT-1 drifts correspond to averages over a 30° longitudinal sector at an altitude of about 600 km. Therefore the altitudinal variation of the vertical drifts [e.g., Pingree and Fejer, 1987; Eccles, 1998] and the relatively large longitudinal averaging of the satellite data need to be taken into account for a detailed comparison of Jicamarca and ROCSAT-1 drifts. Pingree and Fejer [1987] showed that the Jicamarca equinoctial vertical drifts increase with altitude between 2100 and 1300 LT and decrease from 1300 to 2100 LT, with largest increases and decreases (about 0.15 m/s/km) at about 1000 and 1800 LT, respectively. Similar altitudinal variations should occur during other

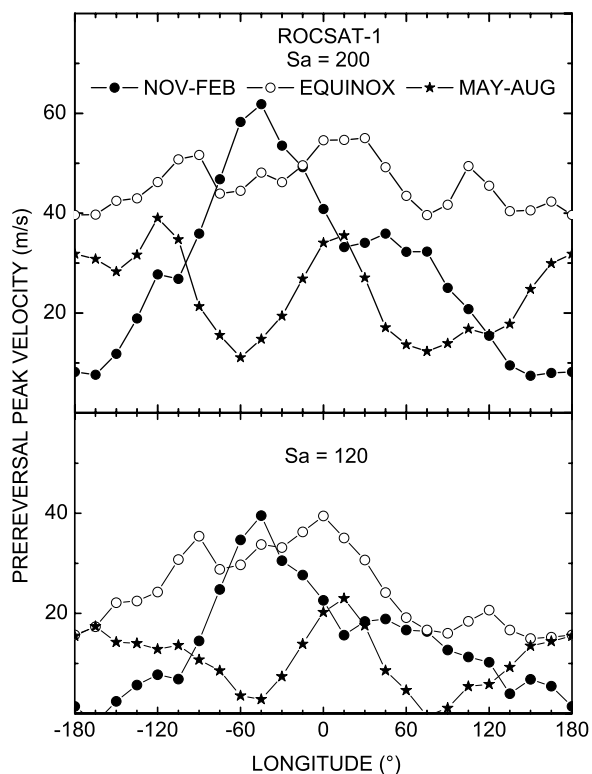


Figure 8. Seasonal and longitudinal variations equatorial evening prereversal velocity peaks for two decimetric solar flux values.

seasons. Figure 9 shows the very good agreement between our results centered over the radar site and the Jicamarca drifts obtained from the Scherliess-Fejer model, even without correcting for altitudinal and longitudinal integration effects.

[28] Our model results are generally in good agreement with the model drifts presented by *Scherliess and Fejer* [1999], especially during equinox. However, the large longitudinal variations of the daytime drifts shown in Figures 4 and 5, and the strong longitudinal effects shown in our solstitial evening drifts were not captured by the Scherliess-Fejer model since the relatively small number of AE-E drift measurements required the use of much larger longitudinal bins. In addition, our results show much larger prereversal velocity enhancements during December solstice and equinox. On the other hand, the solar flux variation of the midnight-noon June solstice drifts derived by *Scherliess and Fejer* [1999] is probably more realistic than that shown in our model. Future comparisons with the eastern hemisphere ground-based and satellite data (e.g., AE-E) should improve the solar flux dependence of these model drifts.

[29] Extensive studies of evening and early night vertical plasma drift velocities have been carried out using ground-based observations in the Brazilian and Indian equatorial regions. Our model drifts are in good agreement with the evening plasma drifts derived from ionosonde measurements over Brazil [e.g., *Batista et al.*, 1996], especially if one considers the generally quite different altitudes and spatial integrations of the corresponding measurements. The satellite data clearly show strong longitudinal variations of

the early night vertical drifts in the American sector during both June and December solstice, which is consistent with the ground-based data. The ROCSAT-1 drifts are also in good agreement with ground-based measurements of evening vertical drifts over India [e.g., *Balan et al.*, 1992; *Sastri*, 1996].

[30] Vertical drifts were measured by the ALTAIR incoherent scatter radar over the Kwajalein atoll (9.4°N, 167.5°E, magnetic dip 7.5°S) over a 25 day period during July–August 1990, when the solar decimetric flux index was about 200 [*Sultan*, 1994, 1996]. These measurements showed an evening prereversal velocity peak of about 45 m/s near 1900 LT, and reversal time of about 2000 LT which are in good agreement with AE-E data [*Fejer et al.*, 1995; *Scherliess and Fejer*, 1999]. In this case, our (higher altitude) data show a peak velocity of about 30 m/s at 1900 LT and a reversal time of 2000 LT. Our model results are also in good agreement vertical drifts measured by the electric field probe on board the San Marco D satellite between April and September 1988 [*Maynard et al.*, 1995].

[31] *Vichare and Richmond* [2005] used the MTIEGCM to simulate the longitudinal variation of the evening vertical drifts at the magnetic equator during equinox, and to study their dependence on various ionospheric parameters. Figure 10 compares the longitudinal variations of the evening prereversal peaks obtained from the ROCSAT-1 data and from the Vichare-Richmond study. The satellite

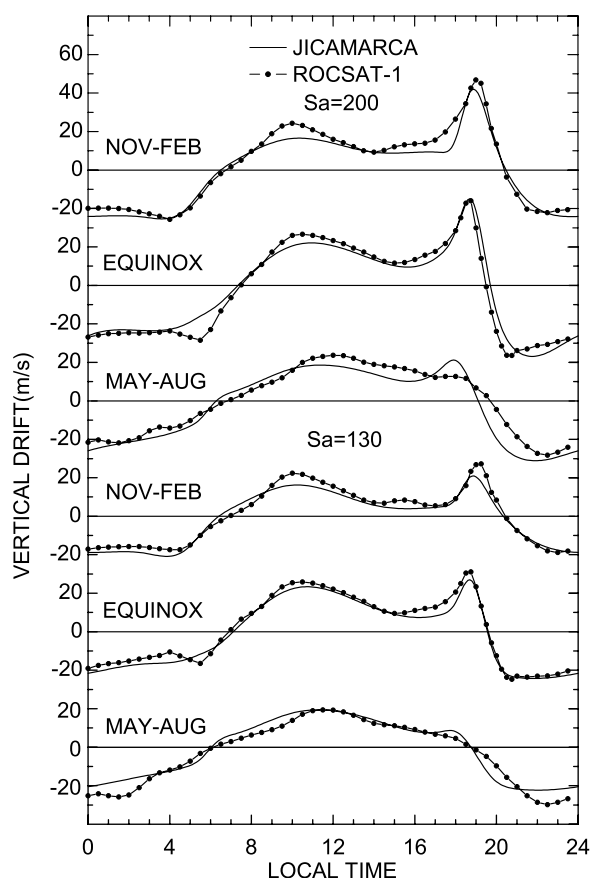


Figure 9. Comparison of ROCSAT-1 and Jicamarca model vertical plasma drifts for two solar flux values.

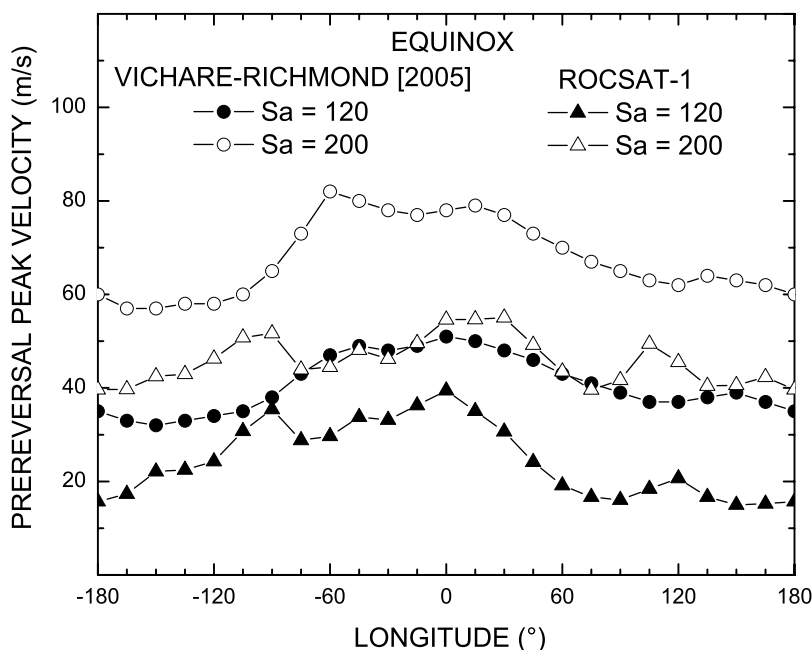


Figure 10. Comparison of quiet time equinoctial evening prereversal vertical velocity peaks obtained from the ROCSAT-1 data and from the numerical simulation by *Vichare and Richmond* [2005].

and simulation data show largest upward velocities in the western Pacific-American sector, but the magnitudes of the simulation drifts are systematically larger than the experimental values. For lower solar flux conditions, the satellite data also show a stronger longitudinal variation. *Vichare and Richmond* [2005] discussed the effects of the zonal wind, field integrated Pedersen conductivity, and magnetic declination on the longitudinal variation of the evening drifts. Our evening velocity peaks appear to maximize in the region of largest field-aligned conductivities and magnetic-east zonal winds.

[32] *Millward et al.* [2001] studied the season, solar cycle, and longitude dependent vertical ion drift velocities using CTIP, which also included the electrodynamic coupling of the equatorial ionosphere and thermosphere. The simulations showed that the daytime vertical drifts are highly dependent on the magnitude and phase of the semidiurnal tidal component, and predicted large downward velocity enhancements (typically about 40 m/s) near dawn during the solstices. The equinoctial evening prereversal velocity peaks showed only small longitudinal variations; the December and June solstice drifts were largest in the American-Atlantic sector, and in the 180°E sectors, respectively. These results, and the predicted variation of the drifts with local time, are generally consistent with our experimental results. On the other hand, the theoretical daytime drifts during high solar flux periods are often much smaller than the measured values; the prereversal enhancements are much longer lasting than observed, and the evening reversal times occur about 2 h later than indicated by our data.

[33] *Kil et al.* [2007] showed that the season averaged morning vertical drifts measured by ROCSAT-1 exhibit a clear wave number-four longitudinal pattern. Our results indicate that this signature is observed during equinox and June solstice and is most pronounced during equinox, which

is in good agreement with DMSP results presented by *Hartman and Heelis* [2007]. We have seen that during December solstice there is a single broad region of enhanced daytime upward drifts in the western hemisphere centered at about 150°W. The seasonal and longitudinal variations of our daytime upward drifts are fully consistent with global distribution of low latitude TEC derived from TOPEX satellite data [*Scherliess et al.*, 2008].

5. Summary

[34] We have developed an empirical model for equatorial *F* region quiet time ($K_p \leq 3$) vertical plasma drifts using ion drift observations on board the ROCSAT-1 from March 1999 to July 2004. This model, which is most accurate during equinox and December solstice, describes in 15° latitudinal bins the diurnal, seasonal and solar cycle variations of equatorial vertical drifts at an altitude of about 600 km for moderate to high solar flux conditions. Our results are consistent with previous ground-based and in situ measurements, but show much stronger longitudinal effects during both day and night. The daytime drifts show strong wave number-four signatures which are most clear during equinox. The longitudinal dependence of the daytime and nighttime drifts is largest during December solstice high solar flux periods. The evening prereversal velocity enhancements and reversal times also exhibit large longitudinal variations, particularly during the solstices. The seasonal and longitudinal dependence of the evening drifts highlights the fundamental importance of the ionospheric conductivity in the electrodynamics of the early night equatorial ionosphere. We believe that this new model, which is available from the authors, provides a considerably more accurate description of equatorial ionospheric electrodynamics.

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