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Key Points:

- Equatorial plasma drifts have large altitude-dependent variability
- The equatorial zonal plasma drifts increase strongly with height below 300 km
- Theoretical models do not account for the height dependence of the zonal drifts

Correspondence to:
B. G. Fejer,
bela.fejer@usu.edu

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Daytime plasma drifts in the equatorial lower ionosphere

Debrup Hui[1] and Bela G. Fejer[1]

[1]Center for Atmospheric and Space Science, Utah State University, Logan, Utah, USA

Abstract We have used extensive radar measurements from the Jicamarca Observatory during low solar flux periods to study the quiet time variability and altitudinal dependence of equatorial daytime vertical and zonal plasma drifts. The daytime vertical drifts are upward and have largest values during September–October. The day-to-day variability of these drifts does not change with height between 150 and 600 km, but the bimonthly variability is much larger in the *F* region than below about 200 km. These drifts vary linearly with height generally increasing in the morning and decreasing in the afternoon. The zonal drifts are westward during the day and have largest values during July–October. The 150 km region zonal drifts have much larger day-to-day, but much smaller bimonthly variability than the *F* region drifts. The daytime zonal drifts strongly increase with height up to about 300 km from March through October, and more weakly at higher altitudes. The December solstice zonal drifts have generally weaker altitudinal dependence, except perhaps below 200 km. Current theoretical and general circulation models do not reproduce the observed altitudinal variation of the daytime equatorial zonal drifts.

1. Introduction

Equatorial plasma drifts play important roles in low-latitude electrodynamic processes including the equatorial electrojet, the equatorial ionization anomaly, and *E* and *F* region plasma irregularities and density structures [e.g., *Fejer*, 1997, 2011]. These drifts are driven by electric fields resulting primarily from the dynamo action of *E* and *F* region neutral winds but can be affected also by low atmospheric and high-latitude ionospheric processes [e.g., *Richmond*, 1995]. Several general circulation models have recently been used to study the climatology and the spatial and short-term variability of the equatorial plasma drifts [e.g., *Maute et al*., 2012; *Liu and Richmond*, 2013; *Liu et al*., 2013].

Equatorial *F* region vertical and zonal plasma drifts have been measured using ground-based radio and radar systems since the late 1960s. Over the last two decades, they have also been measured by in situ satellite probes [e.g., *Fejer et al*., 2008, 2013; *Kil et al*., 2009; *Stoneback et al*., 2011; *Coley et al*., 2014]. The equatorial *F* region vertical drifts are upward during the day and downward at night with typical values of about 20–30 m/s and do not change much with solar flux, season, longitude, and height, except near sunset and sunrise [e.g., *Fejer*, 1997; *Fejer et al*., 2014]. The zonal drifts are westward during the day with typical values of about 40–50 m/s and eastward at night with peak values increasing with solar flux from about 100 to 200 m/s [e.g., *Fejer et al*., 1991, 2005]. The morphology of the equatorial plasma drifts has been described in detail in various review papers [e.g., *Fejer*, 1997, 2011].

Kudeki and Fawcett [1993] showed that the vertical Doppler velocities of daytime coherent echoes from the 150 km region (between about 140 and 170 km) measured at the Jicamarca Radio Observatory (11.9°S, 76.8°W; dip latitude 1°N) correspond to the *F* region vertical drifts. Since August 2001, daytime (between about 0800 and 1600 LT) 150 km region plasma drifts have been measured routinely with the low-power Jicamarca Unattended Long-term Ionosphere and Atmosphere System (JULIA). In a detailed study, *Chau and Woodman* [2004] reported very good agreement between the linearly downward extrapolated *F* region vertical drifts and the JULIA vertical drifts. On the other hand, they observed large differences between the *F* region and 150 km zonal drifts. *Alken* [2009] presented an empirical model of the 150 km vertical drifts using JULIA observations between August 2001 and July 2008. Over the last few years, daytime 150 km vertical drifts have also been measured extensively in the Indian, Brazilian, and Asian equatorial regions [*Patra et al*., 2012, 2014; *Rodrigues et al*., 2013, 2015].

Murphy and Heelis [1986] derived the relationships between low- and middle-latitude plasma drift components resulting from a curl-free electric field. In this case, they showed that the height dependence of the

Table 1. Distribution of Days of Data

	Zonal Drift		Vertical Drift	
	ISR	JULIA	ISR	JULIA
Jan–Feb	9	105	15	154
Mar–Apr	37	42	42	71
May–Jun	34	38	39	109
Jul–Aug	22	143	22	220
Sep–Oct	21	109	38	207
Nov–Dec	17	55	25	204

equatorial *F* region vertical drifts is strongly coupled to the longitudinal gradients (or temporal variation assuming that local time and longitude are interchangeable) of the zonal drifts. *Pingree and Fejer* [1987] showed that *F* region vertical and zonal drifts measured over Jicamarca during a March equinox low solar flux period were consistent with a curl-free electric field. They reported that vertical drifts are highly variable but generally increase (decrease) with height in the morning (afternoon), as expected from the corresponding increase (decrease) of the westward drifts with time. The same altitudinal dependence was inferred from comparisons of the JULIA and the *Scherliess and Fejer* [1999] model drifts [*Alken*, 2009; *Rodrigues et al.*, 2015].

Early studies suggested that equatorial daytime zonal plasma drifts do not change much with height [e.g., *Fejer*, 1991; *Pacheco et al.*, 2010]. Recently, *Fejer et al.* [2013] showed that during the 2008–2011 low solar flux period the daytime westward drifts measured by the Vector Electric Field Instrument on board the Communication/Navigation Outage Forecasting System (C/NOFS) satellite at an average height of about 650 km in the Peruvian equatorial region are larger than the corresponding radar drifts at an average altitude of 400 km. Recently, equatorial measurements between 400 and 1000 km over the 170°–180° longitudinal sector, by the Coupled Ion Neutral Dynamic Investigation Instrument on the C/NOFS satellite, also showed daytime westward drifts increasing with apex height [*Coley et al.*, 2014].

In this work, we use Jicamarca *F* region incoherent scatter and JULIA daytime measurements during geomagnetic quiet periods ($Kp < 3$) low solar flux conditions to study, for the first time, the temporal variability and altitudinal dependence of vertical and zonal plasma drifts in the lower equatorial ionosphere.

2. Measurements and Data

The incoherent scatter radar (ISR) technique used at Jicamarca for *F* region plasma drift measurements was described in numerous publications [e.g., *Woodman*, 1970; *Fejer et al.*, 1991; *Fejer*, 1997], and the current data analysis was described by *Kudeki et al.* [1999]. Incoherent scatter drift measurements cover generally an altitudinal range of 200 to 800 km with a time resolution of 5 min and a height resolution of 15–25 km. The typical accuracy of daytime measurements is about 1 and 10 m/s for the vertical and zonal drifts, respectively. Near solar minimum, the accuracy of these measurements decreases sharply with height above the *F* peak. In this case, the typical measurement errors at about 600 km are of the order of 4 and 50 m/s for the vertical and zonal drifts, respectively. Recently, a new experimental mode has been used for simultaneous plasma drift and density measurements from about 150 to 400 km [e.g., *Chau and Kudeki*, 2013]. We have used only a small number of drift measurements using this observational mode since they have much larger errors. The JULIA drift measurement and data analysis techniques were described by *Chau and Woodman* [2004]. These measurements have usually an integration time of 5 min resolution and accuracies typically better than 1 and 5 m/s for the vertical and zonal drifts, respectively. The databases of Jicamarca incoherent scatter radar and JULIA zonal drifts are smaller than those of the vertical drifts. These data are available at the Jicamarca website (jro.igp.gob.pe/madrigal/).

We used 214 days of *F* region vertical and 184 of *F* region zonal drift measurements during 1997–2014 and 1036 days of vertical and 509 days of zonal JULIA drift measurements from August 2001 to December 2013. These days were selected so that the vertical and zonal drift databases have nearly identical average solar flux values (about 110 solar flux unit (sfu)). Table 1 gives the number of days of our measurements in bimonthly bins. It is important to keep in mind that the incoherent scatter radar and the JULIA drift

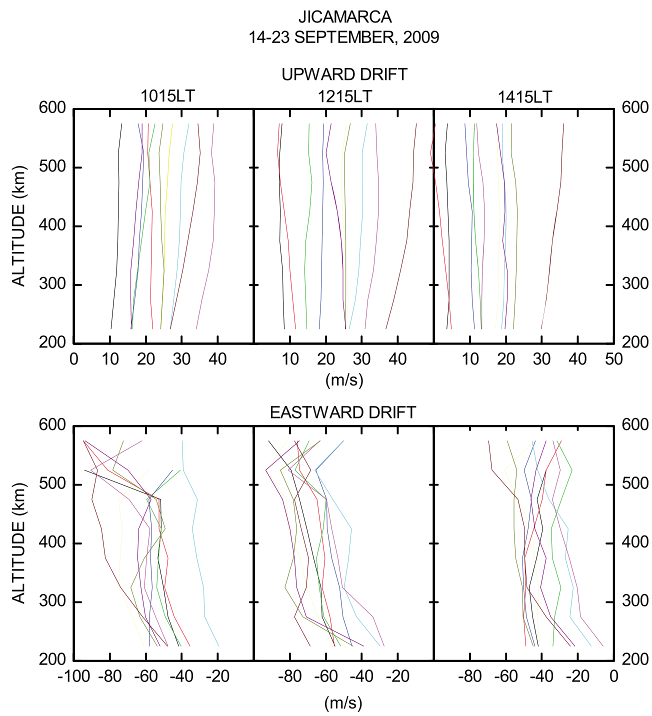

Figure 1. Examples of height profiles of daytime (top row) vertical and (bottom row) zonal drifts over Jicamarca during September 2009. The zonal drifts above 500 km have large errors.

measurements were not made on the same days. We used only quiet time ($Kp < 3$) drifts and did not include measurements during sudden stratospheric warming (SSW) events [e.g., *Chau et al.*, 2009]. Since we have a large number of measurements during very low solar flux values, we deleted vertical and zonal drifts with errors larger than 10 and 50 m/s, respectively, and restricted most of our analysis to altitudes below 600 km for the vertical drifts and below 500 km for the zonal drifts.

3. Results

Figure 1 shows examples of 30 min average height profiles of daytime vertical and zonal drifts during the 14–23 September 2009 very low solar flux (about 71 sfu) period. The zonal drifts above 500 km have much larger errors than at lower altitudes. Figure 1 illustrates the large day-to-day variability of the *F* region daytime vertical and zonal drifts during, which is typical of very low solar flux periods [e.g., *Fejer and Scherliess*, 2001]. Figure 1 also illustrates the small but highly variable altitudinal dependence of the vertical drifts, and the general decrease of the westward drifts with height below about 500 km.

Scatter plots of September–October quiet time JULIA 150 km and *F* region drifts at selected height ranges are presented in Figure 2. The *F* region drifts correspond to 100 km height averages centered at 250, 350, and 450 km. The zonal drift database is smaller at 450 km than at lower heights as a result of our error restriction. The *F* region and the JULIA vertical drifts have comparable variability with standard deviations of about 6 m/s. On the other hand, the JULIA zonal drifts are much more variable (standard deviations of about 22 m/s) than the higher-altitude drifts (standard deviations of about 12 m/s at 250 and 350 km, and about 17 m/s at 450 m/s). Similar results were obtained during other bimonthly periods.

Figure 3 presents the bimonthly averages of the vertical and zonal plasma drifts. In this case, the data at 250 and 400 km correspond to 100 and 200 km averages, respectively, and the 15 min average drifts were smoothed further by three-point running averages. As mentioned earlier, we have not used observations during SSW events, which led to a small number *F* region zonal drift measurements during January–February. The standard deviations and standard errors of the means of the JULIA average drifts are about 8 and 1 m/s for the vertical component and about 55 and 14 m/s for the zonal component. The incoherent scatter average drifts have corresponding values of about 8 and 2 m/s for the vertical and about 14 and 3 m/s for the zonal component. We note that these standard deviations are mostly due to the large quiet time variability and that different binings would result in slightly different averages, especially during periods of small number of measurements.

The *F* region vertical drifts shown in Figure 3 are upward and vary weakly with altitude. These drifts are largest near noon and during September–October, when they have values of about 22 m/s, and smallest during November–December, when they are smaller than 10 m/s. The bimonthly *F* region vertical drifts are consistent with the Scherliess-Fejer season averaged model drifts. On the average, the *F* region vertical drifts increase with altitude in the morning and decrease in the afternoon, in general agreement with the results of *Pingree and Fejer* [1987]. However, the largest vertical drift variations generally occur between about 150 and 250 km, although this could at least be partly due to our nonconcurrent 150 km and *F* region measurements.

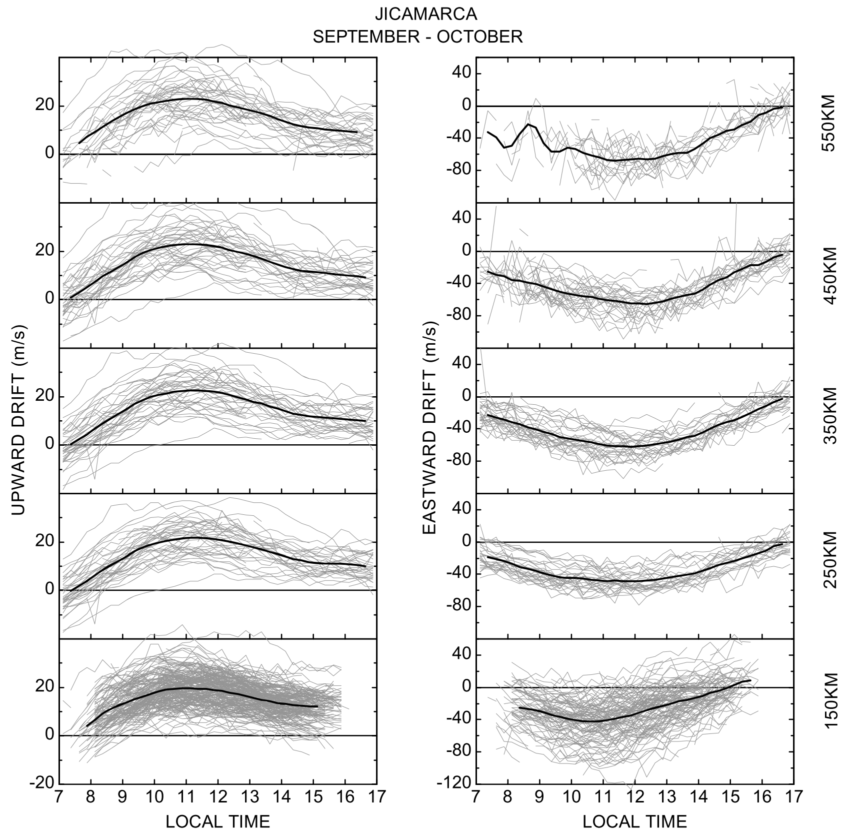

Figure 2. Scatter plots of equatorial daytime (left column) vertical and (right column) zonal plasma drifts measured using the Jicamarca incoherent scatter radar and JULIA during September–October. The thick lines denote the average drifts.

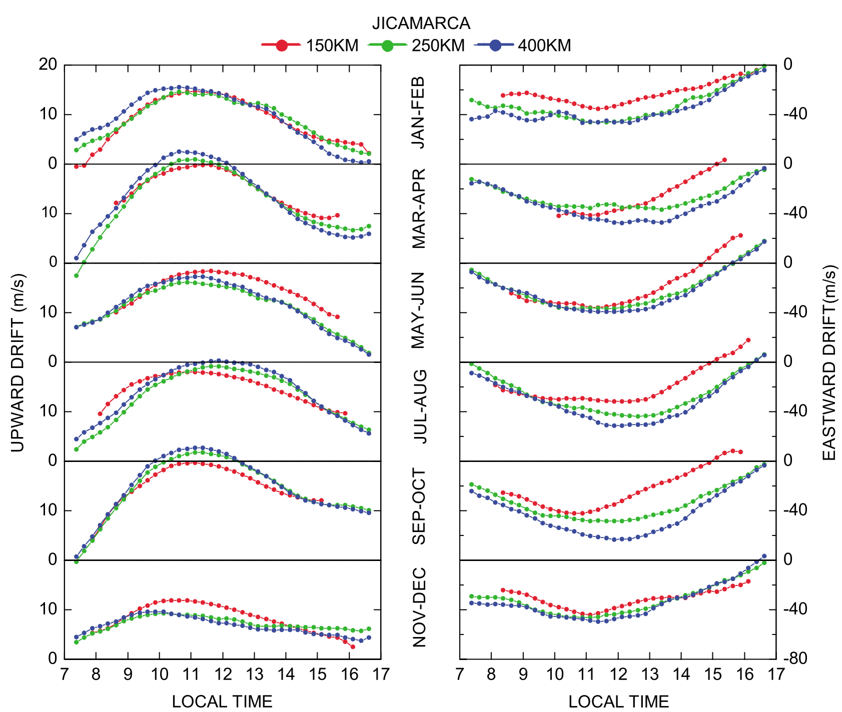

Figure 3. Bimonthly averaged (left column) vertical and (right column) zonal plasma drifts at three altitudinal ranges over Jicamarca during low solar flux conditions.

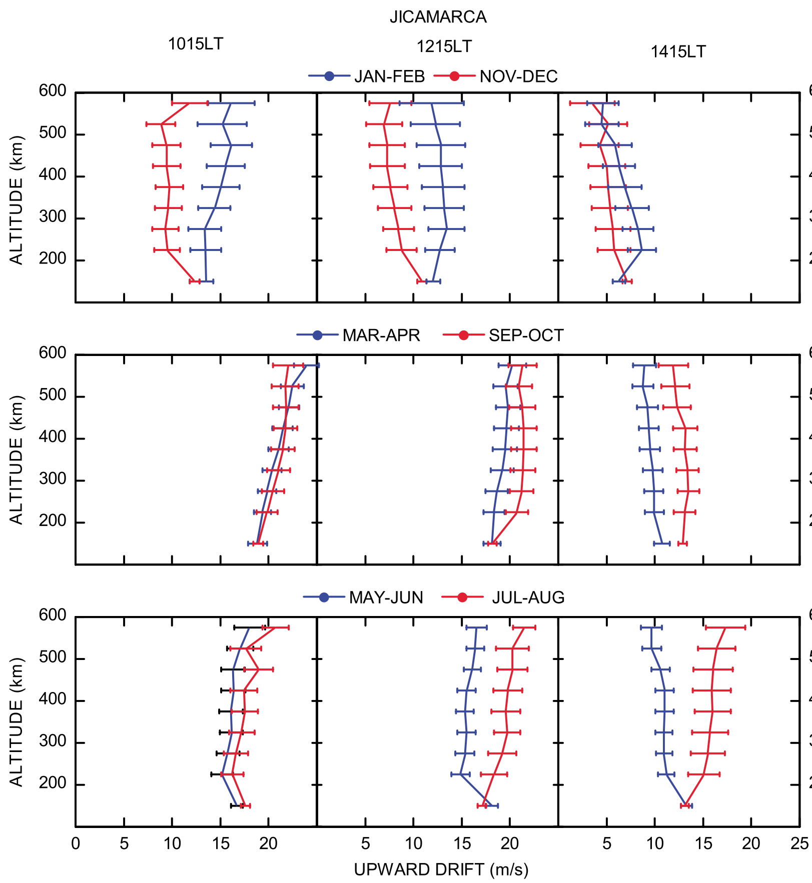

Figure 4. Examples of the altitudinal variations of equatorial plasma drifts obtained from Jicamarca incoherent scatter radar and JULIA measurements. The scatter bars denote the standard errors of the means.

Figure 3 also indicates that the JULIA late morning and early afternoon vertical drifts are larger than the higher-altitude drifts during November–December and May–June, and smaller during July–October.

The zonal drifts are westward with magnitudes increasing with height, except during November–December when they do not change much with height. The largest *F* region westward drifts (about 60 m/s) occur at about 400 km during September–October, and smallest occur during November–February. The 150 km region drifts are systematically smaller than the higher-altitude drifts. This is particularly the case in the afternoon when the westward drifts increase strongly with height between about 150 and 250 km. The zonal drift reversals to eastward occur much earlier in the 150 km region than at higher altitudes, except during November–February.

Figure 4 presents altitudinal profiles of 30 min and 50 km bimonthly averaged vertical drifts at 1015, 1215, and 1415 LT. These data have typical standard deviations of about 6 m/s. In the interpretation of these data it is important to remember that as mentioned earlier, the incoherent scatter radar and the JULIA measurements were not made on the same days. Figure 4 shows much larger bimonthly variability in the *F* region drifts than in the JULIA drifts, especially during the solstices. This variability, which can also be seen in Figure 2, will be discussed in more detail later. The equinoctial drifts increase at about 0.02 m/s/km at 1015 LT; they are nearly height independent at 1215 LT, and decrease with height at 1415 LT. This altitudinal dependence is in good agreement with the low solar flux March equinoctial results of *Pingree and Fejer* [1987]. The *F* region drifts exhibit generally weaker increases in the morning and decreases in the afternoon during June and December solstice months. The June solstice and December solstice 150 km drifts do not match as closely the downward extrapolated *F* region drifts most likely because the JULIA and *F* region drifts were measured during different days. Furthermore, these differences are smaller than the typical standard deviations of these drifts.

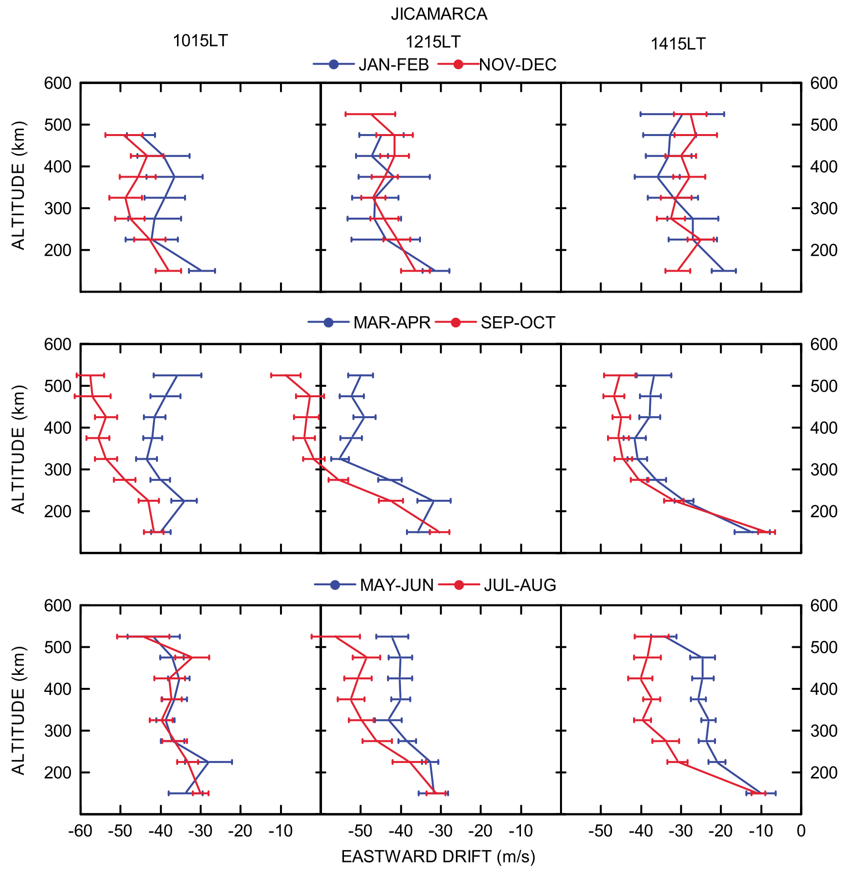

Figure 5. Same as Figure 4 for the zonal drifts. The December solstice plots were obtained using a relatively small number of measurements. The scatter bars denote the standard errors of the means.

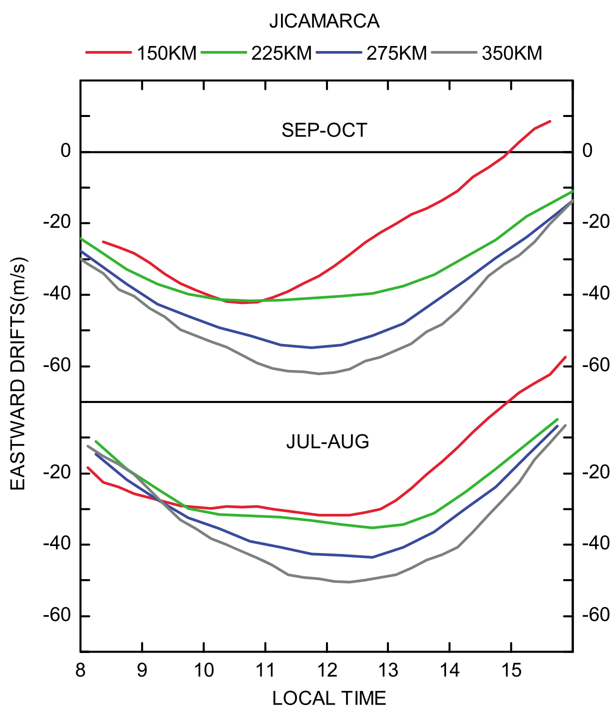

Figure 6. Zonal plasma drifts at four altitudinal ranges for July–August and September–October.

Figure 5 shows height profiles of 30 min bimonthly averaged zonal drifts. The December solstice averages were derived using a relatively small number of measurements, as indicated in Table 1. Figure 5 shows that the daytime westward drifts increase strongly with height below 300 km, especially from March to October, and more weakly at higher altitudes. The largest westward drifts occur above 400 km during September–October, and the smallest occur during December solstice months, when they also have only weak height dependence.

The local time dependence of the daytime zonal drifts during July–October is shown in more detail in Figure 6. The incoherent scatter data correspond to 50, 50, and 100 km averages, respectively, and the 15 min average drifts were smoothed further with three-point running averages. In this case, the standard deviations and standard errors of the means are about 26 and 2.5 m/s for the JULIA drifts and about

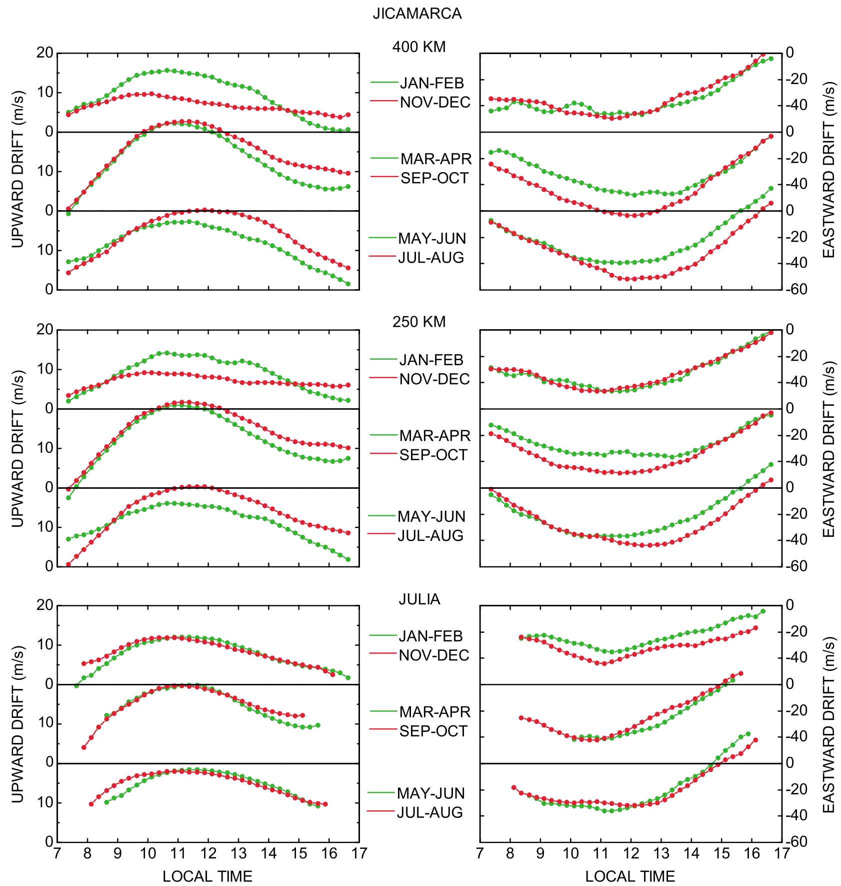

Figure 7. Jicamarca bimonthly averaged *F* region and JULIA (left column) vertical and (right column) zonal plasma drifts.

18 and 3.5 m/s for the *F* region drifts, respectively. Figure 6 shows the systematic increase of the westward drifts with height. These drifts increase weakly with height in the morning, more strongly from 225 to 350 km near noon, and from the 150 km region to 225 km in the afternoon. As shown earlier in Figures 3 and 4, the zonal drifts show weaker altitudinal dependence during from November to June.

The bimonthly vertical and zonal drifts at three altitudinal ranges are compared in Figure 7. The standard deviations and standard errors of the means are about the same as those of the data shown in Figure 3. The 250 km and the 400 km average drifts were obtained using 100 and 200 km altitudinal bins, respectively. The JULIA vertical drifts are essentially identical during the December solstice, June solstice, and equinoctial months, as expected based on the results in Figure 4. In the *F* region, the vertical drifts are generally larger during January–February, September–October, and July–August than during November–December, March–April, and May–June, respectively. Figure 1 also shows that the JULIA zonal drifts are almost identical during the equinoctial and June solstice months, but the January–February westward drifts are about 5 m/s smaller than the November–December drifts. At *F* region heights, the westward drifts are nearly the same during December solstice months but have very large variations during the equinoctial and June solstice months.

4. Discussion

The electrodynamics of the equatorial ionosphere was studied using several theoretical models and numerical simulations. These studies have now accounted for the main features of the *F* region vertical and zonal plasma drifts [e.g., *Eccles*, 1998; *Fesen et al*., 2000; *Milward et al*., 2001] and for the main sources of their quiet time temporal and spatial variability [e.g., *Maute et al*., 2012; *Liu et al*., 2013]. On the other hand, they have not examined in detail the altitudinal dependence of these drifts.

Eccles [1998] developed a model for the low-latitude ionospheric electric field by solving a two-dimensional potential equation with the assumptions of current continuity and equipotential magnetic field lines. They reported electric field structures resulting from divergencies in the neutral-wind dynamo and curl-free effects. The model predicts essentially height-independent daytime vertical drifts. The morning zonal model drifts are eastward at 200 km and westward above 400 km, while the midafternoon drifts are westward with values of about 50 m/s from 200 to 1100 km. Simulations of equatorial plasma drifts for high solar flux equinoctial conditions using the thermosphere-ionosphere-electrodynamics general circulation model (GCM) [*Richmond et al.*, 1992] predicted daytime upward drifts decreasing weakly with altitude, and westward drifts of the order of 60–80 m/s decreasing slightly with height from 100 to 550 km [*Heelis et al.*, 2012; *Rodrigues et al.*, 2012]. These theoretically predicted zonal drift height profiles are not in good agreement with our observations.

Chau and Woodman [2004] presented concurrent daytime observations of incoherent scatter and 150 km drifts during 17–18 December 2003 using a novel experimental mode. They showed good agreement between the 150 km and the average *F* region vertical drifts and even a better agreement with the linearly extrapolated drifts from *F* region altitudinal profiles. *Chau and Woodman* [2004] showed that the 150 km zonal drifts were always smaller than the *F* region drifts, which is consistent with our results. They also reported good agreement between the 150 km zonal drifts and both the *F* region drifts and their linearly extrapolated values in the afternoon, but poor agreement in the morning, in spite of their close temporal variability. Since our 150 km and *F* region drifts were not made simultaneously, our database is not ideally suited for a more detailed study of the relationships between these drifts. On the other hand, our average *F* region altitudinal drift profiles, as well as the results shown in Figure 2, suggest that the assumption of linearly varying zonal drifts is probably not a good one below about 300 km, and that these daytime drifts increase significantly with height. This is also confirmed by studies using C/NOFS satellite measurements [*Fejer et al.*, 2013; *Coley et al.*, 2014].

Chau and Woodman [2004] discussed the morphology of the 150 km zonal plasma drifts using a simple model of equatorial electrodynamics suggested in a private communication by A. D. Richmond. This model, based on the requirement of zero field line integrated current outflow and negligible zonal current density gradients, relates the zonal E × B drift (V_x) to the vertical drift (V_z) and zonal wind velocity (U_n) by

$$V_x \approx \left(\Sigma_H/\Sigma_p\right)V_z + \int\left(\sigma_p \cdot U_n \mathrm{d}s\right)/\Sigma_p$$

where σ_p is the Pedersen conductivity, Σ_H and Σ_p are the field-line-integrated Hall and Pedersen conductivities, and the integrations are along the magnetic field lines. The daytime vertical drifts and Σ_H/Σ_p vary weakly with height, but the Pedersen conductivity is largest in the *E* region. Therefore, *E* region zonal winds should play a major role on the large variability of the 150 km zonal drifts, as suggested by *Chau and Woodman* [2004].

We have shown that while the day-to-day variability of the 150 km and *F* region vertical drifts is nearly identical, the bimonthly drift variability is much larger in the *F* region than at lower altitudes. The zonal drifts have also larger longer-term variations in the *F* region than at lower altitudes. This is consistent with the larger longer-term variability of the *F* region conductivities. *Liu et al*. [2013] studied the day-to-day variability of the equatorial E × B drifts under December solstice solar minimum conditions (70 sfu) using thermosphere-ionosphere-mesosphere-electrodynamics GCM constrained by realistic lower atmosphere wind patterns from whole atmosphere community climate model simulations. This study predicts that lower atmospheric perturbations cause day-to-day variabilities of about 4 and 10 m/s on the *F* region vertical and zonal drifts, respectively. These values are in reasonable agreement with our results.

5. Summary and Conclusions

We have used Jicamarca incoherent scatter radar and JULIA measurements to study the quiet time variability and altitudinal dependence of equatorial daytime plasma drifts. The day-to-day variability of the vertical drifts does not change over this altitudinal range, but their bimonthly and longer-term variability is much larger above 200 km than in the 150 km region. The altitudinal profiles of the vertical drifts are highly variable from day-to-day, but on the average these drifts vary linearly with height. The altitudinal dependence and variability of the equatorial daytime vertical drifts predicted by theoretical and numerical models are in good agreement with our data.

F region daytime zonal drifts are westward drifts with largest values during September–October and smallest from November to February. The 150 km zonal drifts have much larger day-to-day and much smaller bimonthly variability than the drifts above 200 km. From March to October, the bimonthly averaged zonal drifts increase strongly with height below about 300 km, and at much smaller rates at higher altitudes. Over this period, the strongest increases in the westward drifts occur from about 150 to 225 km in the afternoon. The December solstice average drifts do not appear to change much with height, except perhaps below 200 km. The altitudinal variations of the equatorial daytime zonal plasma drifts in the lower ionosphere predicted by current theoretical and general circulation models are not in good agreement with our results. Additional simultaneous plasma drift measurements from about 150 km to *F* region heights and theoretical and simulation studies are needed for a better understanding of the complex variability of lower ionospheric equatorial plasma drifts.

Acknowledgments
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