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Incoherent scatter radar, ionosonde, and satellite measurements of equatorial *F* region vertical plasma drifts in the evening sector

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Abstract. Studies of equatorial *F* region evening vertical plasma drifts using different measurement techniques have produced conflicting results. We examine the relationship of incoherent scatter radar and ionosonde drift observations over the Peruvian equatorial region, and AE-E satellite drifts for different geophysical conditions. Our data show that there is large day-to-day variability on the ratios of radar and ionosonde drifts, but on the average the measurements from these two techniques are in fair agreement during low and moderate solar flux conditions. For high solar activity, however, the Jicamarca evening drifts during equinox and December solstice are significantly larger than the ionosonde drifts. These results can be explained by the different height ranges of the radar and ionosonde measurements, and the increase of the upward drift velocity with height below the *F* region peak. This altitudinal variation is related to the longitudinal gradient of the zonal plasma drifts as a result of the curl-free electric field condition. Our results also indicate that during equinox the increase of the vertical prereversal velocity enhancement with solar activity is largely longitude independent.

1. Introduction

The altitudinal variation of the ionospheric plasma density is strongly affected by vertical plasma motions. In the equatorial ionosphere the *F* region vertical plasma motions result from electrodynamic drifts driven by the zonal electric field. The equatorial *F* region drifts have been studied extensively with incoherent scatter radar observations at the Jicamarca Radio Observatory (12.0° S, 76.9° W; dip 2°N) [e.g., *Fejer*, 1991], ionosonde measurements in the Peruvian, Brazilian and Indian sectors [e.g., *Abdu et al.*, 1981; *Sastri et al.*, 1995], and recently also with satellite data [*Coley and Heelis*, 1989; *Fejer et al.*, 1995].

The vertical drift patterns measured by different probes are generally in good agreement, but the drift amplitudes show some significant unexplained discrepancies. *Fejer et al.* [1995] showed that the *F* region vertical drifts from the Ion Drift Meter (IDM) on the AE-E satellite are consistent with the Jicamarca data. *Sastri* [1995] found fair agreement between these AE-E drifts for the Indian sector, and the Kodaikanal (10.3°N, 77.5°E, dip 4°N) ionosonde drifts. On the other hand, the Jicamarca evening vertical drifts during December solstice and equinox near solar maximum are noticeably larger than the ionosonde drifts derived from observations over the nearby Huancayo Observatory (12.0°S, 75.3°W) [*Fejer et al.*, 1989]. *Rastogi et al.* (1991) suggested that the Jicamarca evening drifts are about 30% larger than the Huancayo ionosonde drifts. *Ramesh and Sastri* [1995] concluded that the *F* region drifts over Kodaikanal have a significantly smaller solar flux dependence than over Jicamarca. *Batista et al.* [1996] reported significant differences between the AE-E evening drifts for the Brazilian sector and the Fortaleza (3.3°S, 33.0°W, dip 4°S) ionosonde drifts.

Vertical drifts play important roles in the electrodynamics of the equatorial and low latitude ionosphere. Therefore, it is important to determine whether the reported discrepancies can be explained by geophysical effects or are due to the measurement techniques. This is the objective of the present study. In the following sections, we give initially a brief description of the measurement techniques, and examine the relationship of radar, ionosonde, and AE-E *F* region vertical drifts. Finally, we explain these observations by taking into account the height ranges sampled in these measurements and the equatorial evening plasma circulation.

2. Measurement Techniques

The Jicamarca incoherent scatter radar measures the vertical *F* region plasma drifts usually between about 250 and 700 km with a height resolution of typically 15 km and with an integration time of 5 min. Here we use the drift values obtained by averaging these measurements near and above the *F* region peak where the signal-to-noise ratios are highest. The accuracy of these measurements is usually about 1-2 m/s [e.g., *Woodman*, 1970].

F region vertical drifts can be derived from ionosonde measurements by determining the time rate of change of h'F (virtual height of the bottomside of the *F* region), $\Delta h'F/\Delta t$, or of heights from constant frequency soundings. The ionosonde drifts correspond to apparent velocities when the reflecting layer is below 300 km since, in this case, they include significant contributions from the chemical decay of the layer [*Bittencourt and Abdu*, 1981]. These height dependent recombination effects result in an overestimate (underestimate) of the true upward (downward) velocities by $V = \beta L$, where β is the loss coefficient, and L is the electron density scale length

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(typically about 10-50 km). When h'F is between 250 and 300 km, this correction is smaller than 5-10 m/s. Here, we discuss ionosonde drifts from 15 min h'F soundings between 1700-2000 local time when they are most reliable, and when h'F is above 300 km.

The IDM measures plasma drift components perpendicular to the satellite track by determining the angles of arrival of the ions (1° corresponding to 140 m/s) [*Hanson and Heelis*, 1975]. The relative and absolute precision of these measurements on the AE-E satellite were about 2 and 7 m/s, respectively. The average altitudes of this satellite during the low, moderate and high solar flux years of 1977, 1978, and 1979 were about 260, 340, and 450 km, respectively. The seasonal and solar cycle variations of the AE-E drifts could only be determined by binning these data in fairly large (about 60°-100°) longitudinal sectors [*Fejer et al.*, 1995].

3. Results

In this section, we use initially simultaneous Jicamarca radar and Huancayo ionosonde drifts. This data base consists of 42 days from April 1968 to October 1979, with decimetric solar flux indices larger than about 120. Examples of these drift velocities are presented in Figure 1. The ionosonde drifts were not corrected for chemical recombination effects since the h'F reflection heights were above 300 km between about 1800 and 2000 local time. Figure 1 shows that the ionosonde and radar drifts can have significantly different amplitudes. On the average, these measurements are usually in fair agreement for low to moderate solar flux conditions (10.7 cm solar flux indices of about 120-140), whereas for higher flux values, the radar drifts are larger (often significantly larger) than the ionosonde drifts during equinox and December solstice. Figure 2 compares the evening prereversal velocity enhancement peaks measured with simultaneous radar and ionosonde observations. These data are plotted only when the radar and ionosonde drift peaks occurred within half an hour of each other, and the ionosonde reflection heights were above 300 km. Figure 2 shows large variability on the ratio between the radar and ionosonde drifts, and that, on the average, the drift velocities from these two techniques are in good agreement for all solar fluxes only during June solstice.

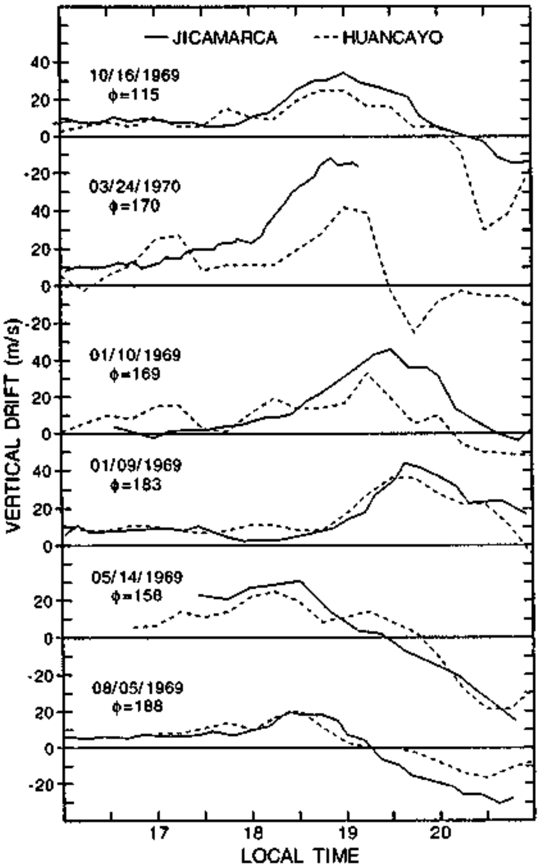

Figure 1. Examples of equatorial upward plasma drift velocities obtained from simultaneous Jicamarca incoherent scatter radar and Huancayo ionosonde observations. Here ϕ denotes the decimetric solar flux index. The ionosonde drifts after about 2000 local time can be strongly affected by chemical recombination effects.

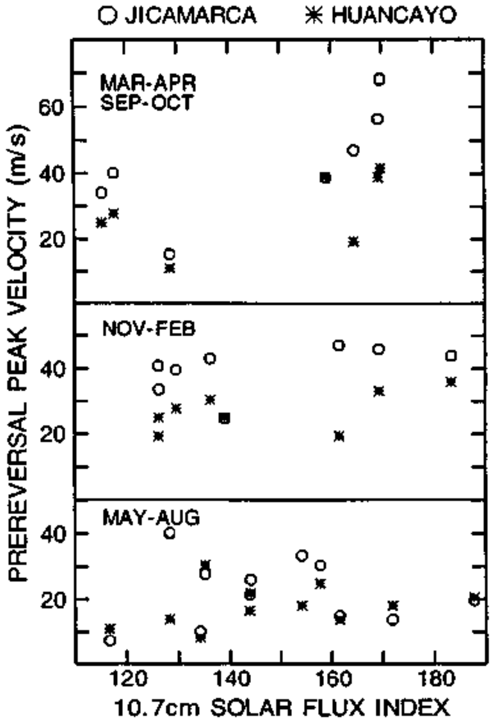

Figure 2. Evening prereversal velocity peaks (positive upward) obtained from simultaneous radar and ionosonde observations.

We can make more detailed comparisons of ionosonde and radar drifts by using all measurements made under similar seasonal and solar flux conditions. This data base consists of more than 200 and 300 days of radar and ionosonde observations, respectively. Figure 3 shows the average afternoon-evening drifts from these two techniques for average solar flux indices of 140 and 200. Again, the radar and ionosonde drifts are consistent during June solstice, whereas the high solar flux equinox and December solstice radar drifts are noticeably larger than the ionosonde drifts. Figure 4 illustrates the good agreement between the ionosonde and radar prereversal velocity enhancement peaks for all solar flux conditions during June solstice, and the solar flux increasing departures between these measurements during equinox and December solstice. The longitudinally averaged equinoctial velocity peaks measured by the AE-E satellite during periods of low, moderate, and high solar activity are also shown. We do not present the AE-E drifts during the solstices when the evening vertical drifts exhibit large longitudinal variations, since this satellite data base is not large enough to determine

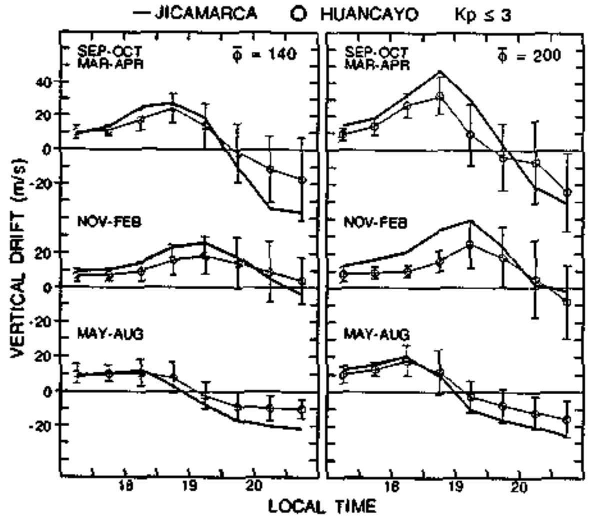

Figure 3. Average equatorial F region radar and ionosonde evening drifts over Peru for moderate and high solar flux periods. These data were obtained by averaging the drifts for solar flux indices of 120 - 160, and 180 - 240, respectively. The scatter bars of the ionosonde drifts are also shown.

solar cycle effects over the Peruvian sector. The AE-E drifts are in good agreement with the Jicamarca equinox data as suggested by *Fejer et al.* [1995]. The ionosonde drifts shown in Figure 4 are consistent with those over India [*Ramesh and Sastri*, 1995]. These results suggest that the solar cycle dependence of the equinoctial drifts do not change much with longitude.

As mentioned earlier, the radar and satellite measurements correspond to heights near the F region peak and above, whereas the ionosonde observations are associated with altitudes in the valley below the peak. Therefore, the results above indicate the occurrence of upward velocity gradients below the F region peak during equinox and December. This is consistent with ionosonde observations over India presented by *Sastri et al.* [1995]. Our data are not well suited for accurate estimates of these altitudinal gradients but, if we assume a height difference of 100-150 km between the radar and ionosonde measurements, the height gradients near the velocity peak would be of the order of 0.1 m/s/km.

4. Discussion

Woodman [1970] suggested that the F region vertical velocities do not change much with altitude except near sunrise and sunset. *Murphy and Heelis* [1986] showed that the assumption of height independent vertical drifts is inconsistent with the curl-free electric field requirement and that even small changes in the height gradient correspond to large variations on the zonal drift pattern. *Pingree and Fejer* [1987] studied the height variation of the Jicamarca vertical drifts during solar minimum using high resolution vertical and zonal drift measurements. The vertical drifts increased with height between about 0800 and 1200 LT, and then decreased up to about 2200 LT with average gradient values of about 0.015 m/s/km. These gradients showed large day-to-day variability, but the average drift pattern was consistent with the curl-free electric field condition at all local times. *Sastri et al.* [1995] showed ionosonde drifts from Kodaikanal (10.3°N, 77.5°E, dip 4°N) and Trivandrum (8.5°N, 77°E, dip 0.6°S), during December solar minimum conditions which increased with altitude below the F region peak near sunset. In this case, the inferred average upward velocity gradient had a maximum value of about 0.05 m/s/km.

The equatorial eastward and downward electric field components are directly related to the upward and eastward drifts, since $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$. Over Jicamarca, a drift velocity of 40 m/s corresponds to an electric field of about 1 mV/m. Assuming a static magnetic field in the meridional plane, and symmetric vertical (v_r) and zonal (v_ϕ) drifts about the equator (i.e., $\partial/\partial\theta = 0$), the curl-free electric field condition can be written [e.g., *Pingree and Fejer*, 1987],

$$1/r\,(\partial v_\phi/\partial\phi) - 2v_r/r + \partial v_r/\partial r = 0 \qquad (1)$$

with $r = R + z$, where r is the radial distance, R is the radius of the Earth, and z is the height. A more general form of the curl-free condition was discussed by *Murphy and Heelis* [1986]. The altitudinal gradient of the vertical velocity can be evaluated from local drift measurements if longitude and local time are interchangeable. Since the second term on the left-hand-side of (1) is usually negligible, the height gradient of the vertical drift is generally related to the temporal variation of the local zonal drift.

The increase of the F region evening eastward drifts with time is consistent with the decrease of the F region vertical plasma drift near the F region peak and above, as suggested by the curl-free condition [*Murphy and Heelis*, 1986; *Pingree and Fejer*, 1987]. Equation (1) indicates that the increase of the upward drift velocity below the F peak should be associated with the decrease of the eastward drift with time near sunset.

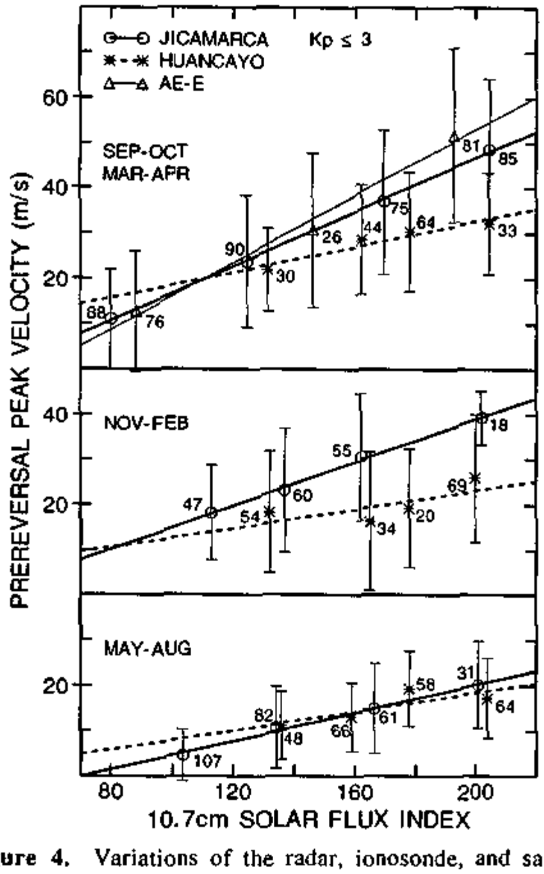

Figure 4. Variations of the radar, ionosonde, and satellite equatorial evening prereversal peak velocities over Peru with the decimetric solar flux index. The scatter bars and number of points are also shown.

The inferred vertical component of the velocity gradient is much larger below the peak than above. When the *F* region peak rises to high altitudes, radar, rocket and satellite measurements and numerical models show, indeed, small eastward or westward drifts in the lower *F* region [*Valenzuela et al.*, 1980; *Kudeki et al.*, 1981, *Tsunoda et al.*, 1981; *Fejer et al.*, 1985; *Haerendel et al.*, 1992]. Over Jicamarca, this occurs typically during equinox and December and for moderate and high solar flux conditions. Preliminary results from a more detailed analysis of the Jicamarca drifts confirm the increase of the vertical drifts below the *F* peak for the conditions reported above. The resulting evening plasma circulation pattern with westward or small eastward drifts and height increasing upward drifts below the *F* region peak, and large eastward and height decreasing vertical drifts above has been inferred initially from equatorial rocket observations by G. Haerendel [private communication, 1980]. Since the zonal and vertical plasma drifts increase with height below the *F* peak, vertical drifts from fixed frequency ionosonde soundings between h'F and the *F* peak should measure velocities closer to the radar values.

The equatorial *F* region plasma drifts result from the actions of the *E* and *F* region dynamos [*Rishbeth*, 1971]. The small altitudinal variation of the Jicamarca vertical and zonal drifts during low and moderate solar flux conditions, and during June solstice also for high solar activity, is probably due to the small prereversal velocity enhancements which produce plasma distributions such that the *E* and *F* region dynamos do not change much with altitude below the peak. If the upward velocity gradients occur only at relatively low altitudes (below about 200-250 km), they will not be easily detected with the radar and ionosonde techniques. Relatively large upward velocity gradients should occur even during solar minimum provided that the *F* region is raised to sufficiently high altitudes as observed by *Sastri et al.* [1995]. Since the prereversal velocity enhancement and the zonal drift pattern have large day-to-day variability, it is not surprising that so does the vertical velocity gradient.

The results derived for the Peruvian region should also be applicable to other longitudinal sectors provided that the different seasonal variations of the evening vertical drifts are taken into account. This study is presently underway.

5. Conclusions

We have shown that in the dusk sector, radar and ionosonde drifts over Peru are in good agreement during June solstice, whereas during equinox and December solstice the radar drifts are increasingly larger than the ionosonde drifts from solar minimum to solar maximum. These results can be explained by taking into account the different height ranges sampled by these two techniques, the curl-free electric field condition, and the *F* region plasma circulation. We concluded that the lower *F* region vertical plasma drifts increase with altitude during equinox and December solstice near solar maximum. The evening drifts are nearly height independent during June solstice for all solar flux values. Above the *F* region peak, the vertical drifts decrease with height independent of season and solar activity.

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