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Global equatorial ionospheric vertical plasma drifts measured by the AE-E satellite

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Abstract. Ion drift meter observations from the Atmosphere Explorer E satellite during the period of January 1977 to December 1979 are used to study the dependence of equatorial (dip latitudes ≤ 7.5°) *F* region vertical plasma drifts (east-west electric fields) on solar activity, season, and longitude. The satellite-observed ion drifts show large day-to-day and seasonal variations. Solar cycle effects are most pronounced near the dusk sector with a large increase of the prereversal velocity enhancement from solar minimum to maximum. The diurnal, seasonal, and solar cycle dependence of the longitudinally averaged drifts are consistent with results from the Jicamarca radar except near the June solstice when the AE-E nighttime downward velocities are significantly smaller than those observed by the radar. Pronounced presunrise downward drift enhancements are often observed over a large longitudinal range but not in the Peruvian equatorial region. The satellite data indicate that longitudinal variations are largest near the June solstice, particularly near dawn and dusk but are virtually absent during equinox. The longitudinal dependence of the AE-E vertical drifts is consistent with results from ionosonde data. These measurements were also used to develop a description of equatorial *F* region vertical drifts in four longitudinal sectors.

1. Introduction

Ionospheric plasma drifts play a fundamental role in the dynamics of the ionosphere and thermosphere. In the equatorial regions, they significantly affect the morphology of the equatorial *F* layer, the evolution of the Appleton anomaly, the generation and evolution of equatorial spread-*F*, the latitudinal variation of thermospheric neutral winds, and the low-latitude protonospheric ion composition [e.g., *Kelley*, 1989]. Plasma drift models have been widely used as input parameters in local and global quiet time and disturbed ionospheric models and also to test predictions from general atmospheric circulation models [e.g., *Anderson et al.*, 1987; *Bailey et al.*, 1993].

Equatorial *F* region plasma drifts have been studied extensively with incoherent scatter radars in the American sector [e.g., *Fejer*, 1981, 1991], and with ionosonde and spaced receiver techniques [e.g., *Basu et al.*, 1980; *Abdu et al.*, 1981]. The ground based measurements suggest large longitudinal variations on the plasma drifts [*Schieldge et al.*, 1973; *Abdu et al.*, 1981; *Fejer et al.*, 1991]. These studies, however, can provide only limited information on the global distribution of the equatorial drifts.

Ion drift meter (IDM) and vector electric field measurements on board polar orbiting and low inclination satellites have recently been used to study the low-latitude *F* region plasma drifts. The longitudinally averaged vertical and zonal drifts from these sources are generally in good agreement with the radar data [e.g., *Maynard et al.*, 1988; *Coley and Heelis*, 1989; *Heelis and Coley*, 1992]. The average perpendicular (approximately vertical) equatorial plasma drift velocities measured by the low inclination (19.76°) Atmosphere Explorer E (AE-E) satellite during equinox near solar maximum showed a diurnal variation largely independent of longitude and which was very similar to that measured at Jicamarca [*Coley et al.*, 1990]. On the other hand, large longitudinal variations of the equatorial vertical plasma drifts at about 1400 LT during the June and December solstices near solar maximum were inferred from f_oF_2 observations on board the Interkosmos 19 satellite [*Deminov et al.*, 1988].

In this work we present a study of the solar cycle, seasonal and longitudinal effects on the equatorial *F* region vertical plasma drifts. We have used IDM measurements from the AE-E satellite taken from January 1976, through December 1979. During this period, the satellite was in nearly circular orbits with the altitude increasing from 230 to 470 km. The data were extracted from the unified abstract (UA) files which contain 15-s averages of the measurements. The satellite data are generally in good agreement with corresponding incoherent scatter and ionosonde drifts. These measurements are used to develop the first global empirical model of equatorial vertical plasma drifts for solar maximum conditions.

2. Instrumentation and Data

The Atmosphere Explorer E made ionospheric measurements from the end of 1975 through June 1981. This satellite, with an orbital inclination of 19.76°, was ideally suited for low latitude ionospheric studies. The characteristics of the IDM are

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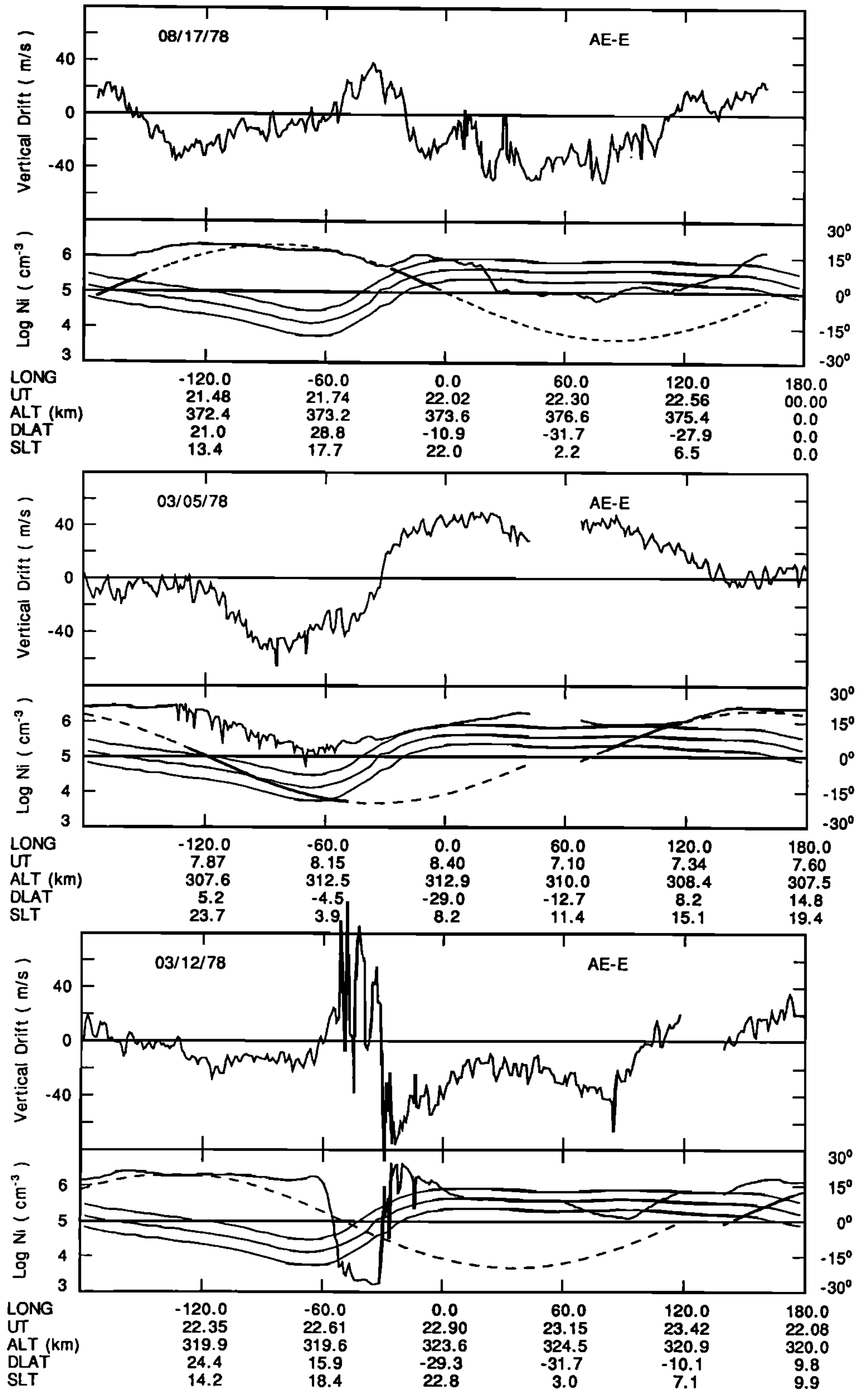

Figure 1. Examples of the vertical plasma drifts (positive upward) and ion concentrations measured by the AE-E satellite. The integration times were 15 s. The bottom panels also show the satellite track (dashed line) and the locations of the dip equator and of the ± 5° dip latitude contours.

described by *Hanson and Heelis* [1975]. The horizontal and vertical ion velocity components perpendicular to the satellite velocity were determined from the arrival angles of the ions, with 1° corresponding to about 140 m/s. The relative and absolute precision of the measurements were about ± 2 and 7 m/s, respectively. The vertical velocity is generally a combination of ion drift components perpendicular and parallel to the geomagnetic field, but near the dip equator it corresponds essentially to the $\boldsymbol{E} \times \boldsymbol{B}$ drift driven by the zonal electric field. The horizontal component, which is a combination of the meridional and zonal drift velocities will not be discussed here. Some of the AE-E IDM data were used earlier by *Coley et al.* [1990] to study properties of the equatorial fountain effect and of the ionospheric dynamo drifts during equinox.

Figure 1 presents examples of vertical plasma drifts and ion concentrations measurements on board the AE-E satellite. The bottom panels show the satellite track (dashed lines), the location of the dip equator and of the ± 5° dip latitudes, and the measured ion concentration. The first example shows the IDM data starting at about 09 solar local time (SLT) near 175° W, whereas in the next two examples the measurements started near 65° W and 145° W, respectively. Notice that the second and third orbits in Figure 1 are wrapped around. The nighttime AE-E measurements show the frequent occurrence of large plasma density dropout near the magnetic equator due to depletions generated by plasma instabilities and/or to satellite crossings of the valley region below the F region peak. The solar cycle, seasonal, latitudinal, and longitudinal variations of large scale (between about 100-200 km) plasma depletions measured by AE-E were discussed by *Fejer et al.* [1993]. These depletions have largest amplitudes in premidnight sector where they are often associated with large irregular drift velocity perturbations. Several late night plasma depletions are shown in the central panel in Figure 1. Satellite crossings of valley region below the equatorial F region peak are usually characterized by plasma density dropouts with large longitudinal extents (over several hundred kilometers) as illustrated in the bottom panel in Figure 1. On these occasions, the satellite drift measurements are frequently unreliable.

We have tried to minimize the effects of velocity fluctuations associated with density depletions (and also with low signal-to-noise ratios) on our average drift patterns by deleting the observations from regions of small ion densities ($N_i < 10^4$ cm^{-3}). In addition, we have also computed the average satellite drifts for $N_i > 5 \times 10^4$ cm^{-3} and $N_i > 10^5$ cm^{-3}. Velocities with magnitudes larger than 100 m/s, which were invariably associated with large plasma depletions or were due to instrumental effects, were also excluded. There were also additional biases in the satellite data. To minimize them, we have not used the drift data measured when the spacecraft was spinning (at about 4 rpm), since this motion may result in a significant bias in the vertical drifts. Our analysis also indicated the occurrence of large dc velocity offsets when the spacecraft was turned on for relatively short periods of time compared to the orbital period (about 100 min). Therefore we have not used the velocity data obtained during periods shorter than 15 min. We will show later that some bias associated with relatively short periods still seems to be present in our data.

Our results indicate the absence of noticeable changes in the diurnal patterns of the seasonally and longitudinally averaged vertical drifts for dip latitude ranges of ± 2.5°, ± 5.0° and ± 7.5°. Thus the results to be presented here were obtained by averaging the vertical drift velocities for dip latitudes between ± 7.5° which are denoted by the thick lines superposed on the satellite track in Figure 1. The use of this relatively large latitudinal range provides a larger number of data points which is essential for the study of solar cycle, seasonal, and longitudinal effects but still keeps any bias of the electrodynamic drifts by field-aligned motions within the variability of the data.

3. Results and Discussion

The equatorial vertical drift velocities measured by the satellite show large variability. In this section we discuss initially the main features of the seasonally and longitudinally averaged drifts, and then proceed to examine their longitudinal dependence.

Solar Cycle Dependence

The solar activity showed a large increase from January 1977 to December 1979 with yearly average 10.7-cm flux indices of 87, 144, and 192, which are typical of low, moderate, and high solar flux conditions. The average altitudes of the satellite during these three years were about 260, 340, and 450 km, respectively. Figure 2 shows the seasonal averages of the satellite vertical drifts during this three year period. The number of data points used in each half hour bin in Figure 2 varied between 41 and 438, had an average value of about 150, with the smallest number of data points occurring generally in 1978. Figure 2 shows that the daytime upward drifts, with average values of about 20 m/s, are independent of solar activity. Since the altitude of the satellite changed by almost 200 km during this period, these results also indicate the absence of significant height variation of *F* region vertical drifts, in agreement with Jicamarca data [e.g., *Pingree and Fejer*, 1987]. The nighttime downward velocities increase slightly with solar activity but are generally smaller than the daytime velocities. The evening prereversal velocity

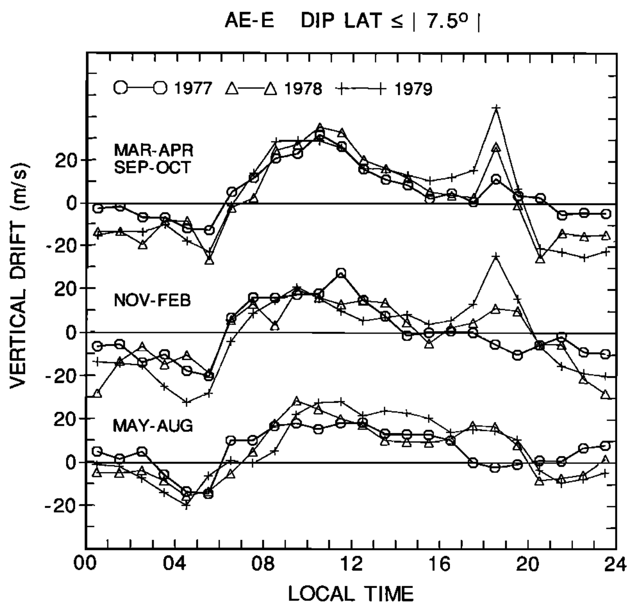

Figure 2. Seasonal averages of the AE-E equatorial vertical drifts for low (1977), moderate (1978), and high (1979) solar flux conditions.

enhancement shows a significant increase from solar minimum to solar maximum particularly during the equinoxes. However, this variation may be overemphasized in these data, since a large upward drift tends to place the *F* peak above the measurement height of 260 km leading to small ion concentrations and to the possible rejection of the data from the database. The dependence of the satellite vertical drifts on solar activity shown in Figure 2 is in good agreement with Jicamarca radar data [e.g., *Fejer et al.*, 1991]. Figure 2 shows that the daytime equinoctial data did not change during this three year period. We will show later that our longitudinal analysis shows larger longitudinal variations of the solstitial than of the equinoctial daytime drifts.

Comparison With Jicamarca Drifts

The seasonally averaged 1977 satellite drifts for relatively quiet magnetic conditions ($K_p<3.3$) and the Jicamarca vertical drifts for comparable (solar minimum) flux indices and geomagnetic conditions are presented in Figure 3. The vertical bars indicate the scatter on the satellite data and not the error on the measurements. The daytime satellite and radar drifts are in good agreement for all seasons, but the nighttime satellite drifts show smaller downward velocities than observed over Jicamarca during the equinoctial and northern hemisphere summer months. The AE-E observations during 1977 were made at relatively low altitudes (average of about 260 km), where nighttime electron densities frequently showed large and sharp depletions, particularly in the premidnight sector and near the June solstice [*Fejer et al.*, 1993]. The nighttime regions of large density dropouts near the dusk sector are often associated with large upward plasma drifts. As mentioned earlier, we have not used the measured drifts when $N_i < 10^4$ cm^{-3}, to minimize the effect of these depleted regions and of data with low signal-to-noise ratios. Since the UA files consist of 15-s averages (corresponding to spatial averages of about 120 km), our nighttime averages could still be affected by drifts from smaller scale plasma depletions. We have also computed the average satellite drifts for $N_i > 5 \times 10^4$ cm^{-3} and $N_i > 10^5$ cm^{-3} which resulted in essentially the same drift patterns as shown in Figure 3. This suggests that our averages are not significantly affected by electron density depletions. Therefore we cannot explain the relatively large difference between the radar and satellite nighttime drifts during the June solstice as due to this or to known instrumental effects.

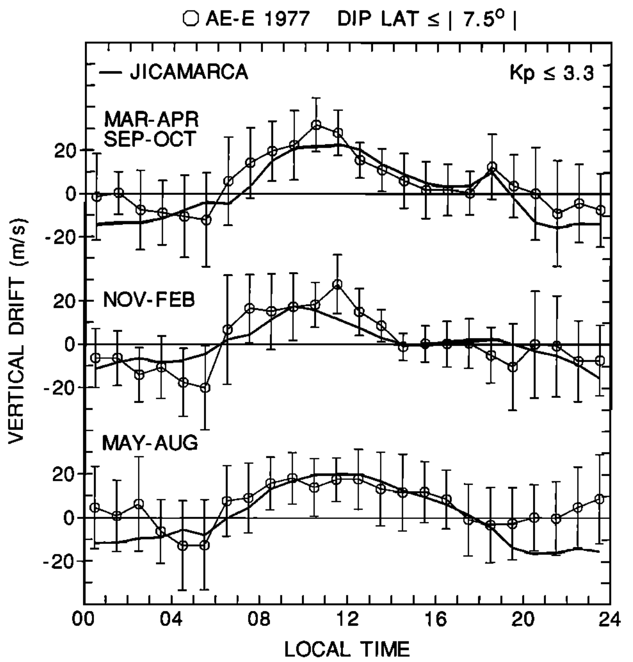

Figure 3. Comparison of longitudinally averaged solar minimum AE-E vertical drifts with corresponding Jicamarca drift during magnetically quiet conditions.

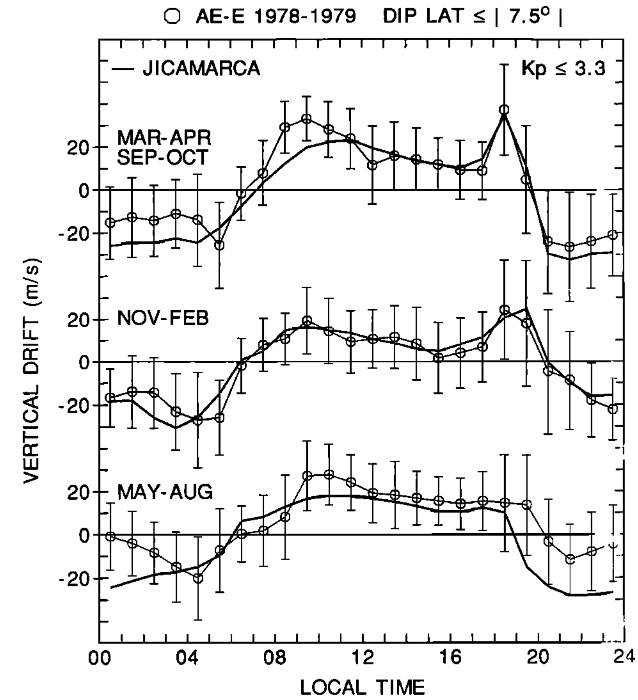

Figure 4. Same as Figure 3 but for moderate to high solar flux conditions.

The solar flux increased rapidly between January 1978 and December 1979. We combined the data from these two years (there were more frequent measurements during 1979 than 1978), which resulted in average solar flux indices between 160 and 180 for all seasons. The data from this 2-year period will be used in the next section to examine the longitudinal dependence of the satellite-observed drifts during moderate to high solar flux conditions. Figure 4 shows the average satellite and Jicamarca drift patterns for moderate-to-high solar flux indices and relatively quiet ($K_p < 3.3$) magnetic conditions. The average satellite drifts follow the radar drift patterns closely during equinox and December solstice. In fact, the agreement between the radar and satellite daytime equinoctial drifts would be even better if we had given more weight to the Jicamarca data from the vernal equinox (the satellite measurements were more numerous during that period). On the other hand, near the June solstice, the Jicamarca data show again appreciably larger downward drifts than measured by the satellite. In addition, during this season, the satellite data indicate an evening reversal time about 1.5 hours later than seen at Jicamarca.

Longitudinal Dependence

Figure 5 presents scatterplots of the 1978-1979 data from four longitudinal sectors representative of the African-Indian

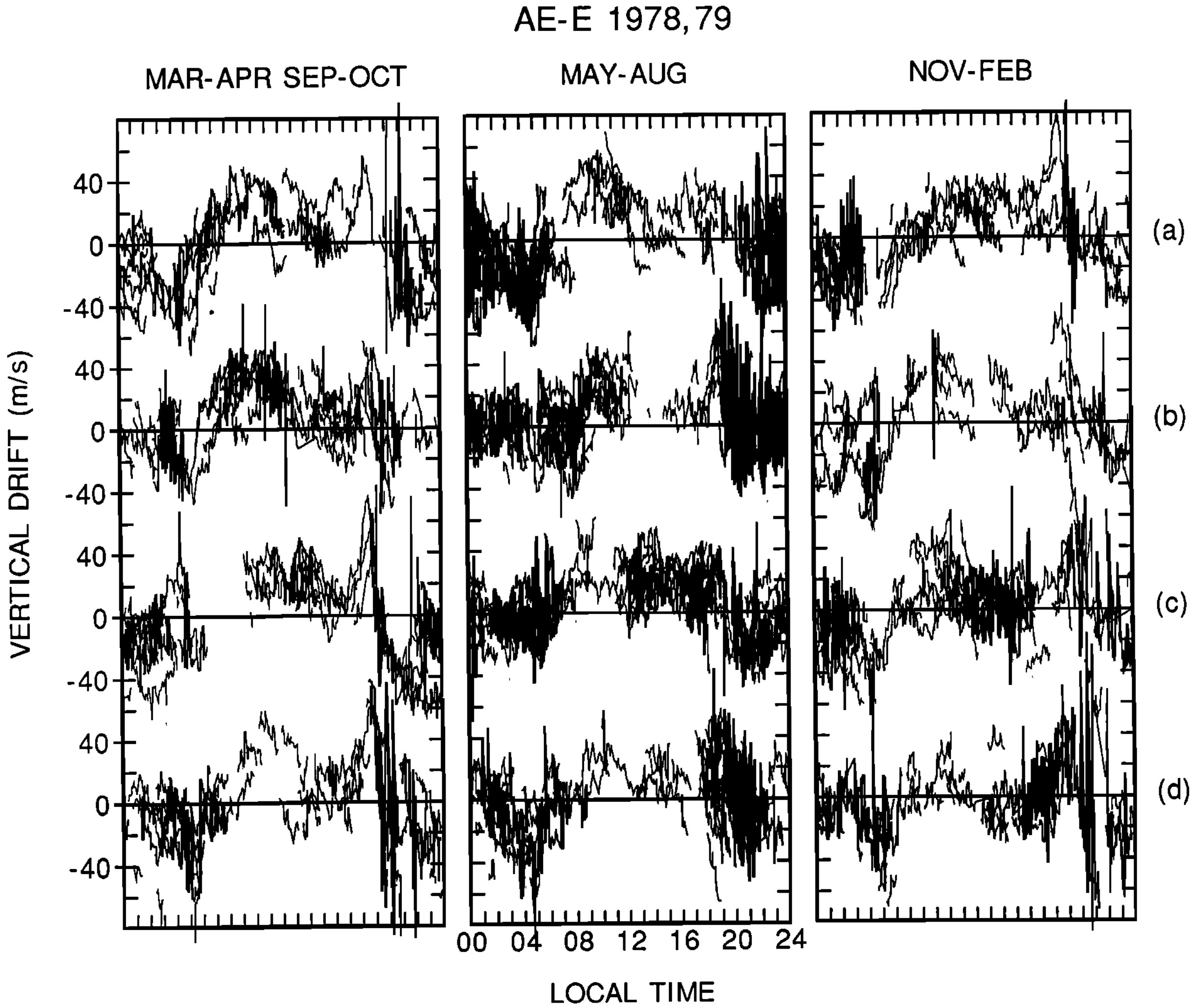

Figure 5. Scatter plot of the 1978-1979 AE-E vertical drifts at four longitudinal sectors representative of the (a) African-Indian (0°-150° E), (b) the Pacific (150°-210° E), (c) the Western American (210°-300° E), and (d) the Brazilian (300°-360° E) equatorial regions.

(0°-150°E) (Figure 5a), the Pacific (150°-210°E) (Figure 5b), the Western American (210°-300°E) (Figure 5c), and the Brazilian (300°-360°E) (Figure 5d) equatorial regions. Figure 2 showed good agreement between the longitudinally averaged equinoctial daytime drift patterns measured during 1977, 1978, and 1979. At some longitudinal sectors, the density of data is barely adequate to examine all the longitudinal sectors. But generally, Figure 5 indicates that the daytime equinoctial drifts do not change much with longitude. The relatively small number of measurements in these sectors during 1977 does not allow us to obtain a reliable estimate of the longitudinal dependence of these solar minimum drifts. Therefore we will not discuss these data here.

Figures 5c and 5d show predominantly downward afternoon drifts during December solstice. However, this feature is not consistent with results from Jicamarca during moderate-to-high solar flux conditions (see Figure 4). To test whether instrumental and/or neutral wind effects were affecting our satellite equatorial drifts, we have also computed the average drifts for the northern and southern magnetic dip latitude bins (corresponding to 7.5° to 0° and to -7.5° to 0°, respectively) for each season and longitudinal sector. The average drift patterns from the northern and southern latitudinal bins were in good agreement for equinox and June solstice for all longitudinal sectors. However, during December solstice, the average daytime (0800 - 1700 LT) drifts from the northern bin exceeded those from the southern latitudinal bin by about 10 m/s in the Brazilian and east American sectors (i.e., in the longitudinal sector between 210° and 360°E). Most of the downward (negative) drift velocities for the December solstice shown in Figure 5 come from the southern magnetic hemisphere in this longitudinal sector. This discrepancy cannot be explained as due to the meridional wind, which is northward during December solstice. We have examined ionosonde and magnetometer data from the Brazilian equatorial region during the November 1978 to February 1979 period when the AE-E satellite had daytime passes in this sector. The ground-based data indicated eastward electrojet currents and *F* region upward plasma drifts consistent with the northern hemisphere data. Comparison of the satellite measurements in the east American sector (210°-300°E) with Jicamarca data also showed much better agreement with the northern hemisphere average drifts. Therefore we conclude that, in this sector, the southern hemisphere (-7.5° to 0°) daytime (0800-1700 LT) drifts should

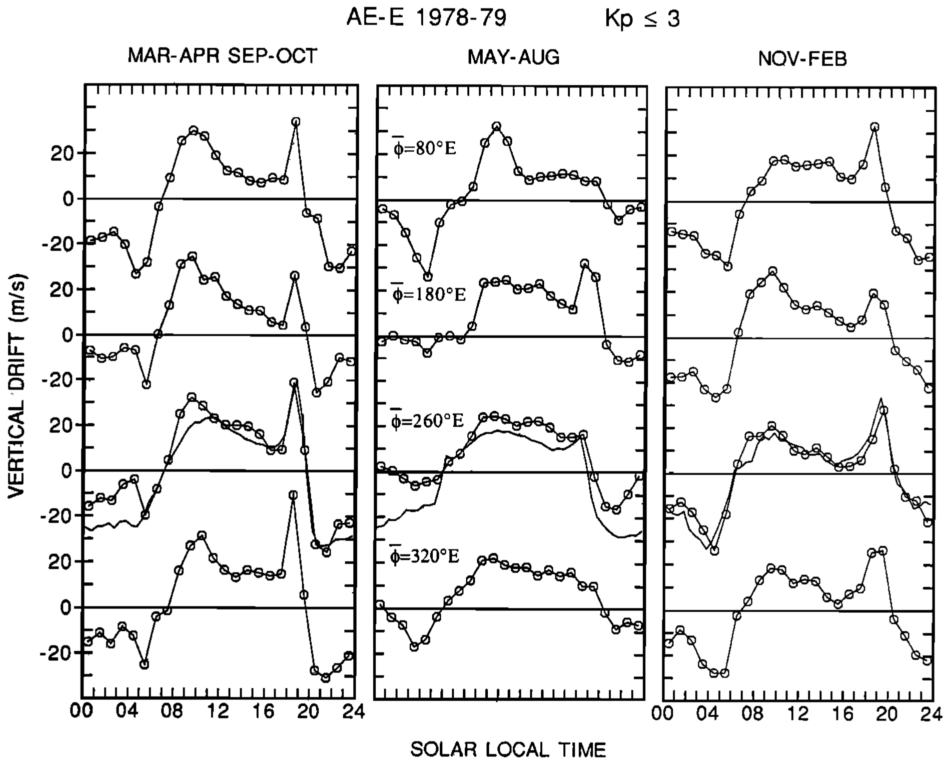

Figure 6. Empirical model of the satellite vertical drifts at four longitudinal sectors for moderate to high solar flux conditions and magnetically quiet conditions. Here $\bar{\phi}$ denotes the average east longitudes. The seasonal Jicamarca drifts patterns for similar solar flux and geomagnetic conditions are also shown.

be increased to bring them into agreement with the northern hemisphere satellite and with the ground-based data. We speculate that this problem with the southern hemisphere daytime drifts near the American sector resulted from the fact that the corresponding measurements were made during relatively short passes when determination of the spacecraft inertial attitude may be less reliable. A dc bias of less than 0.1° would be required to bring the data sets into agreement.

Figure 6 shows the 1978-1979 AE-E *F* region vertical drifts in four longitudinal sectors and the corresponding Jicamarca drifts for similar solar flux and geomagnetic conditions. In this case, we have averaged the data from variable and overlapping longitudinal sectors in order to get good statistics in each sector. The resulting daytime longitudinal sectors covered between 120° and 160°; the evening and nighttime sectors varied between about 60° and 100°. We have also implemented the correction mentioned above for the December solstice daytime drifts in the American sector. Figure 6 shows that the satellite drifts do not change significantly with longitude during equinox and December solstice. Larger longitudinal changes are evident in the average drifts during June solstice. In this case, the largest daytime drifts occur between 0900 and 1100 LT in the Indian sector as seen also in the longitudinal shown in Figure 5a. The June drifts also show the earliest evening reversal time in the east American sector ($\bar{\phi}$=260°E), a strong evening prereversal enhancement in the Pacific sector ($\bar{\phi}$=180° E), and very small downward velocities between 2200 and 0300 LT. Large pre-sunrise downward velocity enhancements are evident at all seasons in most sectors.

The satellite drifts are in excellent agreement with the Jicamarca data during December solstice. The small longitudinal dependence shown in this season results in part from the large overlapping longitudinal bins and from the use of 4-month averages. Notice that Figure 5 shows a very small number of measurements between 150° and 210°E during this season. Furthermore, Jicamarca radar observations and ionosonde data indicate large variations (particularly in the evening sector) in the drift patterns during this 4-month period. The equinoctial drifts also show only a small longitudinal dependence and excellent agreement with the Jicamarca data except for the larger upward and smaller downward velocities in the morning and nighttime sectors, respectively. A large longitudinal dependence is evident in the average drifts during June solstice. The June daytime drifts from the longitudinal sector centered at 260°E are, on the average, about 4 m/s larger than the corresponding Jicamarca drifts. However, most of these satellite measurements came from a sector more than 50° to the west of Jicamarca. The evening drifts during June solstice show the earliest reversal time in the west American sector (260°E), and a large prereversal enhancement in the Pacific (180°E) sector. Notice also the large presunrise downward velocity enhancement in the Indian sector. The nighttime June data again show very small downward velocities between 2200 and 0300 LT. We do not know the reason for this discrepancy.

There were a relatively large number of measurements in the evening sector from May to August. This allows us to examine in more detail the longitudinal variation of the prereversal enhancement drifts, which is presented in Figure 7. Notice the

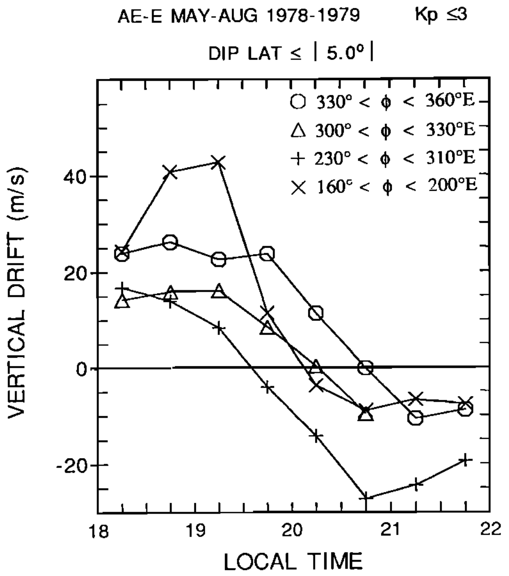

Figure 7. Longitudinal variation of the May-August satellite vertical drifts in the afternoon-evening sector during moderate to high solar flux and magnetically quiet conditions. Here $\bar{\phi}$ denotes east longitude.

decrease of the evening reversal time from the eastern to the western American sector, and the large prereversal enhancement in the 160-200°E sector. These results are in excellent agreement with ionosonde data [e.g., *Abdu et al.*, 1981; *Fejer et al.*, 1991]. The large prereversal enhancement of the June drifts in the 160-200°E sector, for example, is consistent with Kwajalein ionosonde data (R. Tsunoda, private communication, 1993).

Schieldge et al. [1973] used worldwide magnetic variations measured at four universal times on the magnetically quiet day of August 5, 1958, together with a coupled numerical model of global ionospheric dynamo and of the equatorial electrojet. The daily variation of the inferred $\boldsymbol{E} \times \boldsymbol{B}$ electrodynamic drifts at the magnetic equator showed considerable longitudinal variations and also the occasional occurrence of large vertical drifts near sunrise and sunset. *Deminov et al.* [1988] have discussed the longitudinal variation of the upward electrodynamic drift velocity and equatorial electrojet current inferred from peak electron densities measured by the Interkosmos-19 (IK-19) satellite near solar maximum. The vertical drift velocities were calculated for 1400 LT during December and June 1980 using F region peak electron densities for the solution of a simplified continuity equation. Their results suggest that the upward drifts from December are larger than those from June, except for the 180°-300°E longitudinal sector, and that the largest drifts during both seasons occur at about 90° E. This longitudinal dependence of the afternoon solstitial drifts is consistent with the AE-E results. Finally, *Coley et al.* [1990], using a subset of the AE-E data, concluded that the equinoctial equatorial drifts do not have significant longitudinal dependence.

4. Summary and Conclusions

The IDM data obtained on board the AE-E satellite exhibits a great deal of variability. The average drift pattern shows noticeable seasonal and solar cycle dependence. The daytime upward drifts are largely independent of solar flux, but the evening prereversal enhancement shows a large increase from solar minimum to solar maximum. The 1977 satellite measurements were not extensive enough for the determination of the longitudinal dependence of the equatorial drifts near solar minimum. The 1978-1979 observations indicate that the longitudinal variation of the plasma drifts is dependent on season. The equinoctial drifts show very small longitudinal effects. In particular, the evening reversal time and prereversal velocity enhancement do not seem to change with longitude. We expect these results to also hold for solar minimum conditions. The satellite drifts near the December solstice also show only modest longitudinal effects. However, this result could be due in part to the 4-month averages used in this study and to poor statistics in some of the longitudinal sectors. Near the June solstice, large longitudinal effects are evident on the daytime drift patterns, evening reversal times and prereversal velocity enhancements. In the American sector, noticeable drift changes seem to occur in longitudinal sectors as small as 20°-30°. The nighttime data for the June solstice and, to a smaller extent, for equinox show reduced downward velocities compared to similar observations from the ground at Jicamarca particularly between about 2200-0400 LT. We do not know if this is due to some unknown bias or to geophysical effects. Other than this possible bias, the satellite drifts are generally in good agreement with the corresponding drifts measured by the Jicamarca radar and with evening drifts inferred from ionosonde data from Brazil, India, and the Pacific. Previous studies of equatorial F region drifts have been quite limited. However, complimentary data should be forthcoming from vector electric field observations made on board the San Marco satellite during May-August 1988. (N. Maynard, private communication, 1993.)

We have presented a description for the equatorial vertical drifts for moderate to high solar flux conditions. This description should be most accurate for the daytime and evening periods (between about 0600 and 2200 LT) at all seasons. Our measurements were not numerous enough for a detailed study of the satellite drifts during low solar flux conditions. Clearly, additional ground based and satellite observations are needed for a more detailed picture of the global distribution of equatorial ionospheric plasma drifts.

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