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AVERAGE VERTICAL AND ZONAL F REGION PLASMA DRIFTS OVER JICAMARCA

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Abstract. The seasonal averages of the equatorial F region vertical and zonal plasma drifts are determined using extensive incoherent scatter radar observations from Jicamarca during 1968-1988. The late afternoon and nighttime vertical and zonal drifts are strongly dependent on the 10.7-cm solar flux. We show that the evening prereversal enhancement of vertical drifts increases linearly with solar flux during equinox but tends to saturate for large fluxes during southern hemisphere winter. We examine in detail, for the first time, the seasonal variation of the zonal plasma drifts and their dependence on solar flux and magnetic activity. The seasonal effects on the zonal drifts are most pronounced in the midnight-morning sector. The nighttime eastward drifts increase with solar flux for all seasons but decrease slightly with magnetic activity. The daytime westward drifts are essentially independent of season, solar cycle, and magnetic activity.

Introduction

F region incoherent scatter measurements at the Jicamarca Radio Observatory (11.95°S, 76.87°W; magnetic dip 2°N) have provided extensive information on the equatorial vertical and zonal plasma drifts. *Fejer et al.* [1979] determined the seasonal variation of the average F region vertical plasma drifts during solar maximum and minimum using Jicamarca measurements during 1968-1971 and 1974-1977. Recently, the average vertical plasma drifts during the solar maximum periods of 1968-1970 and 1978-1981 were compared by *Fejer et al.* [1989]. This study showed that during solar maxima the effects of magnetic activity (determined by the Kp index) and of solar activity (determined either by the 10.7-cm solar flux or by the sunspot number) on the vertical plasma drifts are season dependent. The average zonal plasma drifts over Jicamarca during solar maximum and minimum were determined previously from observations between 1970 and 1977 [*Fejer et al.*, 1981] and 1970 and 1981 [*Fejer et al.*, 1985]. In these studies, however, it was not possible to determine accurately the variation of the zonal drifts with season and magnetic activity. Recently, DE 2 satellite observations were used to obtain the average low-latitude zonal plasma drifts and the height variation of the equatorial zonal drifts over a large range of altitudes (from about 200 up to 2000 km) [*Aggson et al.*, 1987; *Anderson et al.*, 1987*a*; *Maynard et al.*, 1988; *Coley and Heelis*, 1989]. The equatorial zonal plasma drifts measured by the DE 2 satellite are in general agreement with the Jicamarca data.

The low-latitude electric fields result from complex interactions of E and F region processes which vary considerably from day to night and with season, magnetic activity, and solar flux. Several theoretical and numerical models have been developed to explain the low-latitude dynamo electric fields and currents [e.g., *Rishbeth*, 1971; *Heelis et al.*, 1974; *Richmond et al.*, 1976; *Farley et al.*, 1986; *Takeda and Maeda*, 1983; *Takeda and Yamada*, 1987]. An important characteristic of the equatorial F region vertical drift is the occurrence of a sharp increase of the upward velocity in the dusk sector just before it reverses to its downward direction. This prereversal velocity enhancement, believed to be caused mainly by F region dynamo effects [*Rishbeth*, 1971; *Heelis et al.*, 1974; *Farley et al.*, 1986], is most pronounced during equinox and summer and has large day-to-day and solar cycle variations. The evening upward velocity enhancement is responsible for the rapid rise of the equatorial F layer after sunset which plays an important role on the occurrence of equatorial spread F [*Fejer and Kelley*, 1980].

In this work we present a detailed study of the seasonally averaged vertical and zonal plasma drifts for different levels of the 10.7-cm solar flux and magnetic activity using observations mostly from 1968 through June 1988. We also use measurements of prereversal velocity enhancements up to December 1989. This large data set allows us to determine empirical formulae for the dependence of the evening prereversal enhancement of the vertical drifts, and of the maximum nighttime eastward velocity on the 10.7-cm solar flux and on Kp. Our results should provide considerably more accurate input parameters for global and low-latitude thermospheric, ionospheric [e.g., *Anderson et al.*, 1987*b*, 1989], and protonospheric [*Heelis et al.*, 1990] models.

Results and Discussion

The Jicamarca incoherent scatter radar can usually provide accurate measurements of F region plasma drifts between 250 and 600 km. In this height range the drifts do not change much with altitude except near the evening and morning reversal periods [*Woodman*, 1970; *Fejer et al.*, 1981; *Pingree and Fejer*, 1987]. The values to be presented here represent averages usually between about 300 and 400 km where the signal to noise ratio is highest. The experimental technique was presented by *Woodman* [1970, 1972]. For an integration time of 5 min the typical accuracy of vertical and zonal daytime drift measurements is about 2 m/s and 15-20 m/s, respectively. The nighttime drift measurements have somewhat larger errors as a result of the much lower signal-to-noise ratios (particularly during solar minimum) and, for equinox and summer, also due to the frequent occurrence of spread F echoes. Over Jicamarca an upward (eastward) drift velocity of 40 m/s corresponds to an eastward (downward) electric field of about 1 mV/m.

Vertical Velocities

Figure 1 shows the average quiet time ($Kp \leq 2^+$) F region vertical (positive upward) drifts for equinox (March, April, September, October), winter (May through August), and summer (November through February) for three levels of the 10.7-cm solar activity (Sa) obtained by averaging the velocity measurements in half-hour bins. Here we have used 367 days of observations from 1968 to June 1988. This data set does not have measurements during 1979 and 1982-1983.

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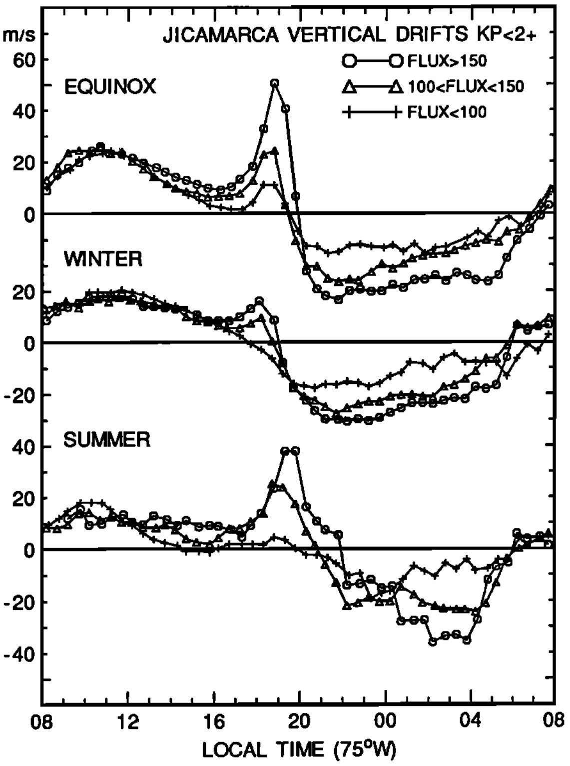

Fig. 1. Average vertical plasma drifts measured at Jicamarca during equinox (March-April, September-October), winter (May-August), and summer (November-February) for three levels of solar flux.

The average fluxes for the days of observations in the first two flux intervals were about 80 and 125 (in units of 10^{-22} W m^{-2} Hz^{-1}) for all seasons. In the third range, the average fluxes were 194, 168, and 174 for equinox, summer, and winter, respectively. The average drifts for Sa<100 and Sa>150 shown in Figure 1 closely resemble the solar maximum and minimum results of *Fejer et al.* [1979] where data from disturbed periods were included in the averages and slightly different seasonal periods were considered. However, the equinoctial and summer prereversal velocity enhancements for Sa>150 shown in Figure 1 are considerably larger than the values reported by *Fejer et al.* [1979]. The daytime average drifts maximize at about 1100 LT with largest values during the equinoxes and smallest during the summer solstices. The daytime drifts do not change much with solar flux, but the evening upward and nighttime downward velocities increase considerably from solar minimum (Sa<100) to solar maximum (Sa>150). The evening enhancements of the vertical velocity (eastward electric field) seem to result from the faster decrease of the E region ionospheric conductivity after sunset compared to the F region conductivity [*Farley et al.*, 1986]. The increase of the prereversal enhancement with solar activity is due to the corresponding increases of the equatorial zonal wind and of the ratio between the magnetic field averaged Pedersen conductivities in the F and E regions. *Goel et al.* [1990] suggested that the increase of the E region conductivity gradient near dusk from solar minimum to the maximum is also partly responsible for the increase of the prereversal velocity enhancement with solar flux.

The equatorial vertical plasma drifts (driven by zonal electric fields) are strongly affected by magnetic activity [e.g., *Fejer*, 1986]. However, *Fejer et al.* [1989] showed that during solar maxima the average Jicamarca vertical drifts for $Kp > 3$ and $Kp \leq 2^+$ are only slightly different except near sunset. The velocity perturbations during disturbed times result from the penetration of high-latitude electric fields into the low-latitude ionosphere [e.g., *Fejer*, 1986] and/or from disturbance dynamo effects [*Blanc and Richmond*, 1980]. The low-latitude perturbations associated with large and sudden changes in high-latitude convection are usually short-lived (1-2 hours) and, therefore, tend to cancel out on the averaged data. Furthermore, there are considerable day-to-day variations of the vertical drifts even during magnetically quiet periods [*Fejer et al.*, 1989]. Finally, the Jicamarca drift data set does not contain a large number of measurements during strongly disturbed (say, $Kp \geq 5$) periods. We have examined the average drifts for $Kp \leq 2^+$ and $Kp > 3$ for different seasons and periods of the solar cycle and noticed that for the seasonally averaged drifts, magnetic activity effects are most evident in the winter solar minimum period. The average vertical velocities during quiet and disturbed periods for the solar minimum months of May and June 1974-1977 are shown in Figure 2. In this case the average vertical velocities during quiet and disturbed periods are significantly different, particularly near dawn and dusk. The larger upward (downward) velocities near dusk (dawn) are consistent with an increase in the penetration of high-latitude electric fields associated with an increase in convection [e.g., *Fejer*, 1986].

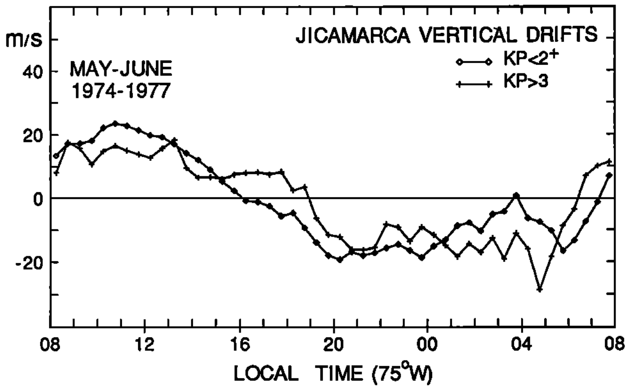

Fig. 2. Average vertical plasma drifts for quiet and disturbed conditions for May and June during solar minimum.

Figure 3 shows the variation of the peak of the prereversal velocity enhancement as a function of solar flux using data from 1968 through 1989 and also the corresponding least squares fitted curves. In this case we have binned the peak velocities for flux levels of 60-80, 80-100, 100-120, 120-140, 140-180, 180-220 and >220. The bars indicate the standard deviation of the averages and not the error bars. The velocity peaks increase linearly with the flux during equinox. The winter data show negative velocities for small values of the solar flux. Of course, these negative velocities do not correspond to velocity peaks, but to the values of the drifts at the (season dependent) time of the prereversal velocity enhancements (see Figure 1). These downward velocities were included for completeness. The winter data show a better fit to a quadratic curve, but saturating for large flux values. This is consistent with the solar maximum results of *Fejer et al.* [1989]. The summer data could be fitted equally well by either a linear or a quadratic curve. The average prereversal velocity peaks shown in Figure 1 are smaller than the corresponding average values obtained from Figure 3. This is not surprising, since the prereversal enhancement of the average velocities is always smaller than the average of the prereversal velocity enhancements. This is particularly the case for the solstices, when the times of occurrence of the prereversal velocity peaks change rapidly.

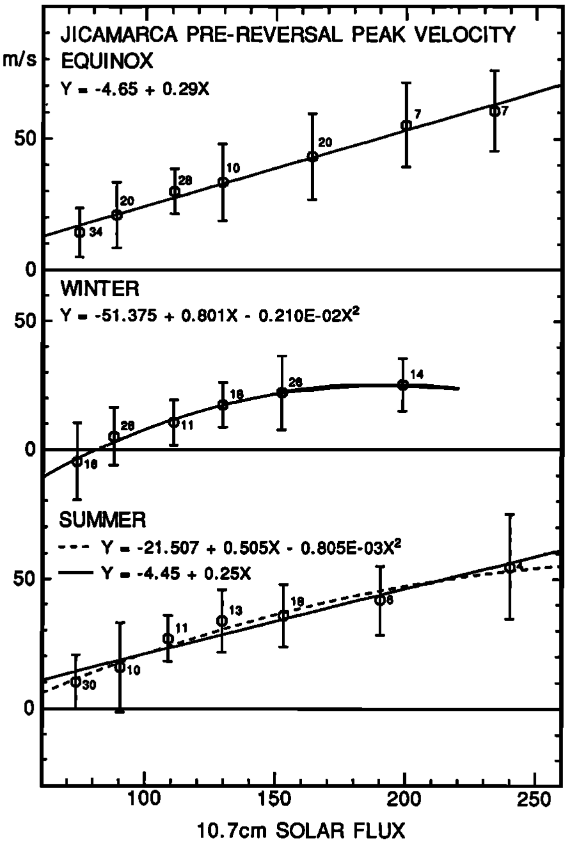

Fig. 3. Variation of the evening average prereversal vertical velocity with solar flux. The standard deviation and number of points used in each average are also shown.

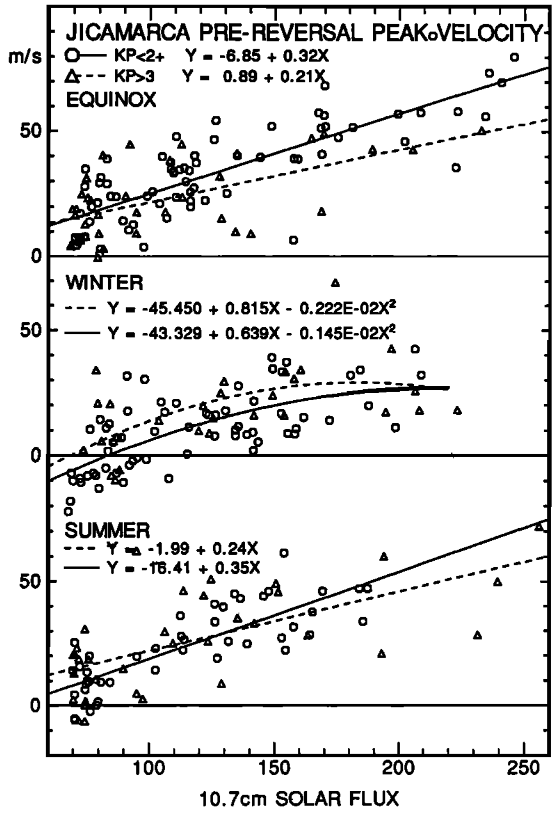

Fig. 4. Prereversal velocity peaks as a function of solar flux for two levels of magnetic activity.

Fejer et al. [1989] showed that during solar maxima the prereversal peak velocity decreases with magnetic activity during equinox and increases during winter. Figure 4 shows the variation of the prereversal enhancements with solar flux for two levels of magnetic activity and the corresponding least squares fitted curves. This figure also illustrates the scatter of the evening peak velocities. For the winter data, part of the scatter is a result of the variation of the amplitude of the prereversal velocity enhancement from May-June to July-August which is particularly pronounced for low solar fluxes. The large degree of scatter in Figure 4 does not allow us to give much significance to the increase and decrease of the peak velocities with magnetic activity during equinox and winter, respectively. However, these results are consistent with the dependence of the corresponding average evening upward drifts on magnetic activity during solar maximum [*Fejer et al.*, 1989]. The increase of the prereversal velocity enhancement with magnetic activity for low flux levels during winter is also seen in Figure 2. We have no explanation for the different variations of the evening upward drifts with Kp at different seasons.

Namboothiri et al. [1989] studied the variation of the vertical plasma drifts over Trivandrum [8.5°N, 77°E; magnetic dip 0.9°S] obtained from HF Doppler observations. Their results indicate an increase of the prereversal velocity enhancement with solar activity consistent with the Jicamarca data. The HF Doppler measurements also suggest that the prereversal velocity peak decreases as magnetic activity changes from quiet to moderate conditions (Ap ~15-20), but increases well above the quiet time values for high magnetic activity. In their study, however, the effect of magnetic activity was not done separately for each season. Our data set does not have a large enough number of measurements during very disturbed periods to allow us to provide reliable results on the possible increase of the prereversal velocity peak during periods of very high magnetic activity.

The daily variation of the average vertical velocities obtained at Jicamarca is probably not representative of variation of the velocity at other longitudinal sectors. Large longitudinal variations of the equatorial F region vertical plasma drift velocity in the evening sector can be inferred from ionosonde measurements of the time variation of h'F (virtual height of the bottomside of the F layer) [e.g., *Abdu et al.*, 1981]. Although conventional ionosonde measurements do not provide accurate plasma drift measurements most of the day, they determine precisely the evening reversal times of the vertical drifts. Figure 5 shows the longitudinal variation of the dip equator, and the evening reversal times of the vertical plasma drifts during solar maximum as determined from ionosonde observations from four longitudinal sectors. The reversal times from the Huancayo h'F observations are in excellent agreement with the results from Jicamarca. The data in Figure 5 indicate that the use of the Jicamarca vertical drift data as an input parameter for modelling studies at other longitudes will likely result in large errors in the evening sector, particularly for the June solstice.

Zonal Velocities

Fejer et al. [1981, 1985] showed that the daytime F region westward plasma drifts do not change significantly with solar flux but that the nighttime eastward velocity increases with solar activity. These results were obtained by averaging data from all seasons. Our data base is now considerably larger than that used in these previous studies. Therefore, we can determine also the average seasonal patterns and magnetic activity effects with considerably more accuracy. We have

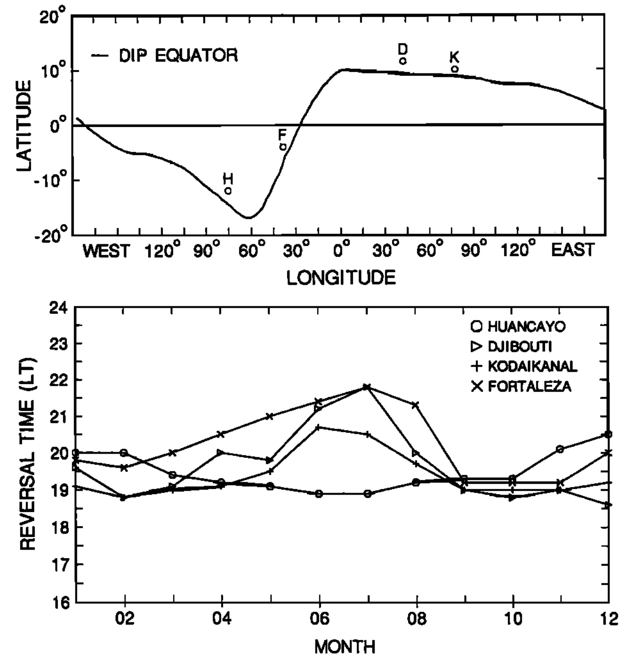

Fig. 5. Longitudinal variation of the location of the dip equator, and time of the evening reversal of the equatorial vertical drifts at four stations determined from ionosonde observations.

used 175 days of observations from 1970 to June 1988, but with no measurements during 1979 and 1982-1983. In addition, there is a considerably smaller number of drift measurements in the midnight-sunrise period.

Figure 6 shows the effect of solar flux on the average zonal drifts for each season. The average 10.7-cm solar fluxes for the observing days during equinox, winter, and summer were 89, 90, and 84 for the period of low solar activity, and 181, 166, and 153 for the period of high solar activity. There were only a few observations between 0600 and 0800 LT during summer months of high solar activity. Therefore, the corresponding average values might not be typical. As mentioned above, the zonal drift data have larger errors and statistical fluctuations than the vertical velocity data. Therefore, we have used a three-point running average to smooth out the fluctuations from the half-hour averages. The daytime westward drifts do not change much with season and also with solar flux, except perhaps during equinox. The daytime zonal drifts are driven by E region electric fields at slightly higher latitudes which are coupled to the F region along the highly conducting magnetic field lines [e.g., *Fejer et al.*, 1981]. The daytime westward drifts are significantly smaller than the nighttime eastward drifts, leading to a superrotation of the equatorial ionosphere [*Woodman*, 1972]. Satellite observations indicate that the superrotation decreases with increasing latitude [e.g., *Maynard et al.*, 1988; *Coley and Heelis*, 1989].

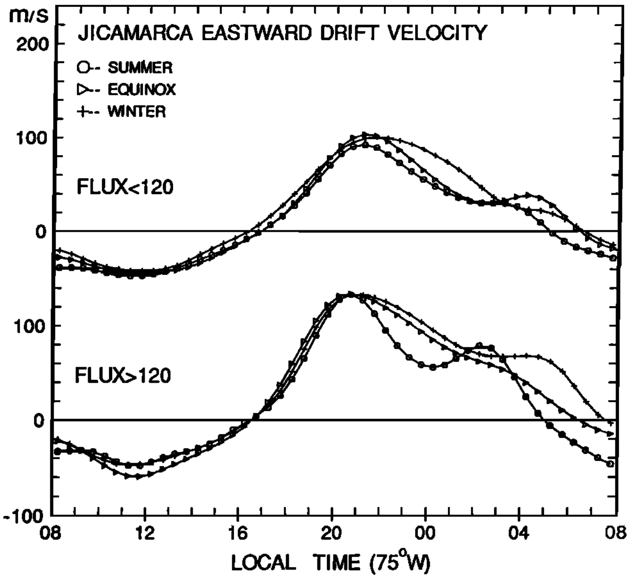

Fig. 6. Seasonal variations of the zonal plasma drifts during periods of low and high solar flux.

The evening and nighttime eastward velocities increase with solar flux at all seasons. The eastward drifts are largest during local winter and smallest during summer. However, we should keep in mind that average fluxes were different during the three seasons and that the data show considerable day-to-day variations. Figure 6 also shows that the reversal times of the zonal drifts are nearly independent of solar activity, except for the winter morning reversal time, which seems to increase with solar flux. The morning reversal time occurs latest during winter and earliest during summer. The summer data for Sa>120 show a well-pronounced postmidnight peak. A similar eastward velocity peak is also evident on the equatorial zonal neutral wind and plasma drift data measured on board the DE 2 satellite [*Wharton et al.*, 1984; *Herrero et al.*, 1985]. The DE 2 equatorial wind and drift measurements from 1800 to 2200 and 0600 to 1000 MLT were made primarily during solstice but biased toward December because of the large number of observations during December 1981 [*Maynard et al.*, 1988; *Coley and Heelis*, 1989]. The satellite data show a reversal of the zonal winds at about 0500 LT which is in good agreement with our summer results.

For equinox we have a large enough number of measurements to determine the average drifts for periods of low, medium, and high solar fluxes. Figure 7 show these drifts for average solar flux values of 78, 123, and 204, respectively. The increase of the morning reversal time between solar maximum and minimum is consistent with the results of *Fejer et al.* [1981, 1985]. Figure 7 also shows that during solar maximum the maximum eastward velocity increases up to about 160 m/s.

We have seen that the maximum eastward velocity peaks increase with solar cycle in similar fashion for all seasons. Figure 8 shows the change of the maximum eastward velocity peak with solar flux. In this case the average velocities from 2030 to 2115 LT for all days of observations were binned in the flux intervals 60-80, 80-120, 120-160, and larger than 160, and the average velocities in these intervals were plotted

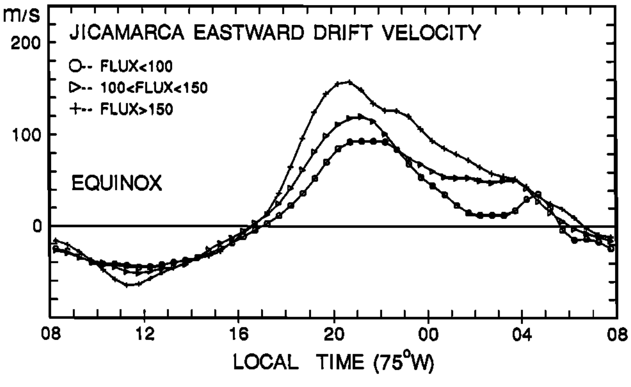

Fig. 7. Average zonal plasma drifts during equinox for low, moderate, and high solar fluxes.

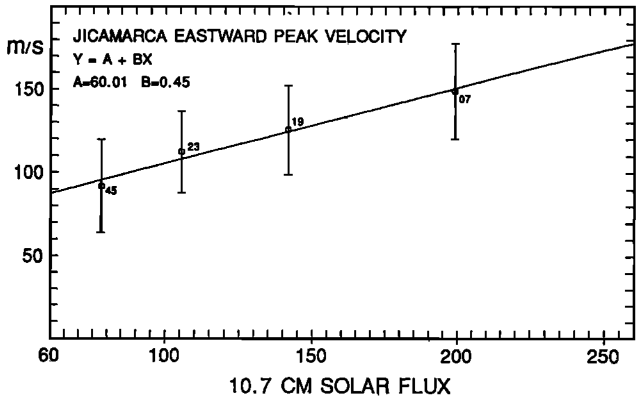

Fig. 8. Dependence of the peak zonal velocity on the 10.7-cm solar flux. The standard deviation and number of points used in each average are also shown.

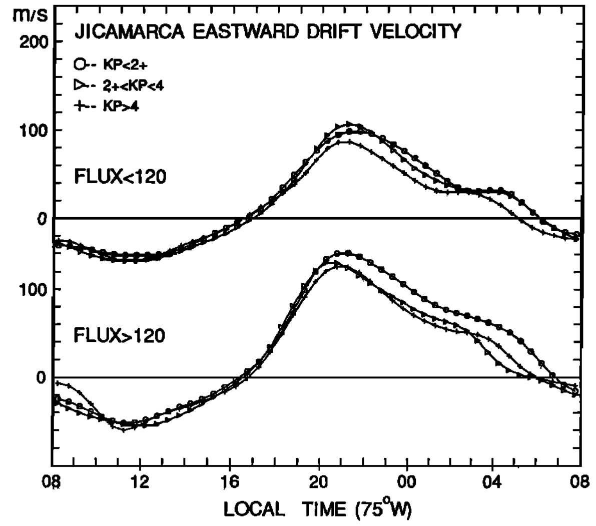

Fig. 9. Average zonal velocity for three levels of magnetic activity during periods of low and moderate to high solar fluxes.

for the corresponding average fluxes. There are only a few observations during periods of very large solar fluxes. The eastward peak velocity increases linearly with flux, but there is a large scatter of the peak velocities. The scatter is due in part to the different rates of increase with solar flux at different seasons and to magnetic activity effects. However, there are also considerable day-to-day variations even during magnetically quiet periods. Recently, *Berkey et al.* [1990] showed that the maximum nighttime eastward velocity over Arecibo increases by about 20 m/s between solar minimum and maximum. The rate of increase of the Arecibo eastward velocity with solar flux is about one third of the rate shown in Figure 8. The Arecibo average drifts show a maximum eastward velocity of about 50 m/s at 2000-2100 LT during solar maximum and a reversal from eastward to westward drifts about 4 hours earlier than at Jicamarca.

We can also determine the effect of magnetic activity by averaging the data from the different seasons. A large data base is necessary to determine this effect, since the zonal plasma drifts show considerable variability even during magnetic quiet conditions. The variation of the average zonal plasma drifts for three levels of magnetic activity is shown in Figure 9. The number of drift measurements during very disturbed days is relatively small. Our results show that the daytime and early evening drifts are essentially independent of magnetic activity, in agreement with the results of *Fejer et al.* [1981]. The daytime F region plasma drifts are determined essentially by the E region zonal winds, since the large daytime conductivities short circuit F region polarization electric fields [*Rishbeth*, 1971; *Heelis et al.*, 1974]. Therefore, these results indicate that daytime zonal winds do not change much with season, solar activity, and magnetic activity. The decrease of the nighttime eastward velocities with Kp shown in Figure 9 is consistent with disturbance dynamo electric field effects [*Blanc and Richmond*, 1980]. Low-latitude zonal drift perturbations due to the penetration of high-latitude electric fields are essentially negligible [*Fejer*, 1986]. *Ganguly et al.* [1987] showed that during disturbed periods the Arecibo zonal drifts show a westward velocity with largest amplitudes in the late night-early morning sector, as would be expected from the disturbance dynamo process. On the other hand, spaced receiver VHF polarimeter measurements of F region plasma bubbles in the Brazilian low-latitude region during spread F conditions suggest a substantial increase of the eastward velocity in the premidnight sector during disturbed conditions [*Abdu et al.*, 1985]. Therefore, the zonal velocities of the equatorial F region plasma bubbles in the premidnight sector do not always correspond to the velocity of the ambient plasma.

Conclusions

Extensive incoherent scatter radar measurements at Jicamarca were used to determine the variation of the equatorial vertical and zonal plasma drifts with season, solar cycle, and magnetic activity. The F region drifts show largest variation in the evening and nighttime periods. The prereversal enhancement of the vertical drifts is maximum during equinox, when it increases linearly with solar flux but decreases with magnetic activity. The prereversal enhancement increases with magnetic activity during winter but seems to saturate for large flux levels. Our results suggest that the daytime F region drifts and, therefore, the corresponding E region electric fields and winds are nearly independent of solar activity. The daytime zonal drifts are also independent of season and magnetic activity. The nighttime eastward drifts increase with solar activity by about the same factor at all seasons but decrease with magnetic activity. The afternoon reversal time of the zonal drifts is season independent, but the morning reversal time occurs earliest during summer at latest during winter. The Jicamarca data are not representative of the drifts in other longitudinal sectors, particularly during the southern hemisphere winter.

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