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Equatorial F-region zonal plasma drifts

Bela G. Fejer, *Utah State University*
E. Kudeki
D. T. Farley

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Equatorial *F* Region Zonal Plasma Drifts

B. G. FEJER, E. KUDEKI,[1] AND D. T. FARLEY

School of Electrical Engineering, Cornell University, Ithaca, New York

We have examined in detail the *F* region plasma drifts measured at Jicamarca, Peru, during 1978–1981, a period of high solar activity, and compared these drifts with Jicamarca data taken during periods of lower activity, as well as with other equatorial zonal neutral wind and plasma drift measurements. The increase in solar activity causes larger nighttime eastward plasma drifts at Jicamarca and delays the morning reversal time from eastward nighttime to westward daytime drifts. The radar data seem to be in good agreement with nighttime neutral wind measurements made by the DE-2 satellite, but are systematically smaller than spaced receiver drifts measured with both the scintillation and the VHF polarimeter techniques. For integration times of 20–30 min (but perhaps not for shorter integrations), the Jicamarca zonal plasma drifts, measured with both the incoherent scatter and the radar interferometer technique, change little with altitude near the *F* region electron density peak and above. However, at nighttime, below the *F* peak, there is a clear shear in the zonal plasma drifts, with decreasing eastward drifts below the *F* peak reversing to westward drifts at lower altitudes. The nighttime profiles of the equatorial plasma drifts are in good agreement with the results from recent numerical models of the equatorial ionosphere.

INTRODUCTION

In the last few years, there has been a growing interest in the study of low latitude *F* region zonal plasma drifts and neutral winds. These parameters are important for understanding the dynamics and thermal balance of the thermosphere and ionosphere, and perhaps also the generation and evolution of equatorial spread *F*.

Equatorial *F* region zonal plasma drifts have been observed with the Jicamarca incoherent scatter radar near Lima, Peru (11°57′S, 76°52′W, magnetic dip 2°N) since 1970. *Woodman* [1972] described the experimental technique and presented the initial results which showed westward drifts during the day with a maximum of about 50 m/s and eastward drifts at night with a maximum of the order of 130 m/s. *Fejer et al.* [1981] discussed the results from measurements made during 1970–1977. They showed that the daytime plasma drifts change very little with season and solar cycle. The nighttime maximum eastward plasma drifts changed from about 130 m/s to about 105 m/s between 1970–1971 and 1974–1977. These two periods were considered to be typical of solar maximum and minimum conditions, respectively. The east-west drift velocities also seem to be independent of geomagnetic activity [*Woodman*, 1972; *Fejer et al.*, 1981].

Over the last few years nighttime plasma drift measurements during periods of equatorial spread *F* have also been performed using a radar interferometer technique developed for ionospheric measurements at Jicamarca [*Farley et al.*, 1981; *Kudeki et al.*, 1981]. The interferometer drifts agree well with the incoherent scatter drift data and confirm the existence of a strong shear in the height profile of the *F* region zonal plasma drifts in the evening–early night period. This shear had been suggested earlier by ion cloud release experiments during twilight hours [*Valenzuela et al.*, 1980] which showed eastward plasma drifts near the *F* region peak and above and westward drifts at lower altitudes.

Detailed observations of ionospheric plasma drifts have been made for a number of years by recording the fading of echoes from radio waves using spaced receivers [*Chandra et al.*, 1970; *Rastogi et al.*, 1972]. The velocities observed in this way are of the same order as the Jicamarca drifts at night, but are appreciably larger during the day [*Fejer et al.*, 1981]. Extensive nighttime zonal plasma drift measurements of equatorial spread *F* irregularities have been performed recently using both spaced receiver scintillation data and spaced receiver VHF polarimeter data [e.g., *Basu et al.*, 1980; *Yeh et al.*, 1981; *Abdu et al.*, 1985]. These measurements give maximum nighttime eastward drifts usually between 150 and 250 m/s.

Airglow observations have also been used to study *F* region winds, either by tracking 630.0 nm nightglow depletions [*Weber et al.*, 1978; *Carman*, 1983; *Sobral et al.*, 1985] or by Doppler measurements with Fabry-Perot interferometers [*Sipler and Biondi*, 1978; *Sipler et al.*, 1983; J. W. Meriwether et al., unpublished manuscript, 1985]. The measured nighttime low latitude east-west neutral wind velocities obtained in these ways are usually about 100–150 m/s. Low latitude neutral thermospheric winds have also been measured from 200–700 km by the Dynamics Explorer 2 satellite [*Wharton et al.*, 1984].

The quiet time ionospheric *F* region plasma drifts at middle and low latitudes are driven mainly by *E* and *F* region dynamo electric fields. Several theoretical and numerical models have been developed to explain the equatorial *F* region east-west plasma drifts [e.g., *Rishbeth*, 1971; *Heelis et al.*, 1974; *Richmond et al.*, 1976; *Anderson and Mendillo*, 1983; *Takeda and Maeda*, 1983]. The most recent studies have also provided height profiles of the zonal plasma drifts which can be directly compared with the velocity profiles measured at Jicamarca.

In this paper we examine, initially, the variation of the height averaged *F* region east-west plasma drifts with solar cycle. This is an extension of the work by *Fejer et al.* [1981], who compared the solar minimum drift data of 1974–1977 with data from 1970–1971. This latter period was neither as close to the peak of the solar maximum nor as representative of a period of very large solar activity as the period of 1978–1981 examined here. In addition, we will compare our results with drift measurements obtained with the spaced receiver scintillation technique at Ancon, Peru, and with wind data measured with the DE-2 satellite during the same period of

[1] Present affiliation is Department of Electrical and Computer Engineering, University of Illinois, Urbana.

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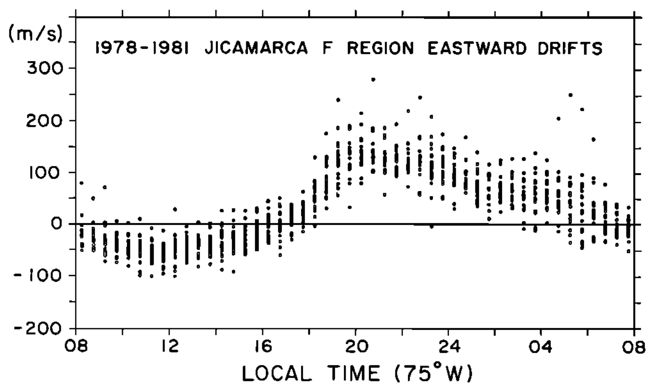

Fig. 1. Jicamarca 1978–1981 *F* region incoherent scatter plasma drifts organized in 15 min bins.

the solar cycle. The second part of this paper will examine the height variation of the *F* region east-west drifts. We will show that for integration times of about 20 min and longer, the drifts change little with height, except in the sunset-midnight period in the *F* region valley region, where both incoherent scatter and radar interferometer observations indicate a pronounced shear in the zonal flow. On the other hand, for integration times of about 5 min, the drift data sometimes show large fluctuations during both daytime and nighttime. Finally, we compare the daily variation and the height profile of the Jicamarca drifts with the results from numerical models of low latitude plasma drifts.

Experimental Procedure

Most of the *F* region zonal plasma drifts to be discussed here were measured with the 50 MHz incoherent scatter radar at Jicamarca. The antenna is split into two beams, both perpendicular to the earth's magnetic field, and pointed 2.45° to the east and 4.33° to the west of vertical. The vertical and east-west drifts are obtained by combining the two line of sight velocities. The drifts are usually measured from 200 to 900 km with a resolution of 25 km. The integration time is about 5 min, and the estimated errors in the east-west drift measurements are about 15 m/s during the day and somewhat larger at night, depending on the signal to noise ratio. The accuracy decreases in regions of reduced electron density. Usually only a single value is quoted for the *F* region velocity at a particular time. This value is usually an average of the data between 300 and 400 km, where the signal to noise ratio is the highest and where, consequently, the measurements are most accurate. During solar maximum, however, particularly in the evening–early night period and at equinox and local summer, the height range for the most accurate drift measurements can be considerably higher since the *F* region electron density maximum is sometimes at 600 km or above as a result of large presunset upward plasma drifts [e.g., *Fejer*, 1981]. When spread *F* echoes are present over a limited range of altitudes in the sampling region, the altitude range of the most reliable drift measurements is also changed accordingly. Over Jicamarca an eastward *F* region drift velocity of 40 m/s corresponds to an upward electric field of about 1.0 mV/m. The experimental procedure for the Jicamarca drift measurements is described in more detail by *Woodman* [1972].

When spread *F* echoes are present, plasma drift measurements can be made with the radar interferometer technique [*Farley et al.*, 1981; *Kudeki et al.*, 1981] by following the motion of individual discrete scatterers through the antenna beam. Usually the full 50 MHz antenna is used for transmission and the east-west quarters are used separately for reception. The typical height and temporal resolutions are 5 km and 1 min, respectively. When spread *F* echoes occur over a large range of altitudes, a height interval extending over 600 km can be sampled simultaneously with this interferometer procedure. The initial results of *F* region plasma drifts during periods of spread *F* were published in the work of *Kudeki et al.* [1981].

Results

In this section we present initially the results of the height averaged drifts obtained with the incoherent scatter technique at Jicamarca during the solar maximum period of 1978–1981 and compare them with the results of *Fejer et al.* [1981] and also with zonal plasma drifts and neutral winds obtained with other techniques. Then we present some results on the height variation of the plasma drifts obtained with both incoherent scatter and radar interferometry.

Jicamarca Height Averaged F Region Drifts

Figure 1 shows a scatter plot of the east-west drifts obtained from 38 days of data taken during 1978–1981. Most of the measurements were made during 1980–1981; very little data from 1979 was available. The variation of the drifts is due only partly to statistical instrumental effects. The drifts are westward during the day with a typical value of about 50 m/s. The nighttime eastward drifts are considerably larger with values of about 150 m/s at 2100 local time. The evening and morning reversals occur at about 1700 and 0700 local time.

The average east-west drifts measured during 1978–1981 are compared with the results from 1970–1971 and 1974–1977 in Figure 2. The average sunspot numbers during the months of these observations for the three periods 1970–1971, 1974–1977, and 1978–1981 were about 80, 25, and 170, respectively. Therefore, the 1978–1981 average corresponds to a period of considerably higher solar activity than studied previously. We can see that the daytime drifts and the evening reversal time do not change much with solar activity. The nighttime drift velocity, however, increases considerably with increasing solar activity, and the morning reversal time is delayed by 1–3 hours.

Fejer et al. [1981] pointed out that the zonal plasma drifts show considerable day to day variability, but do not change significantly with season or short term fluctuations in mag-

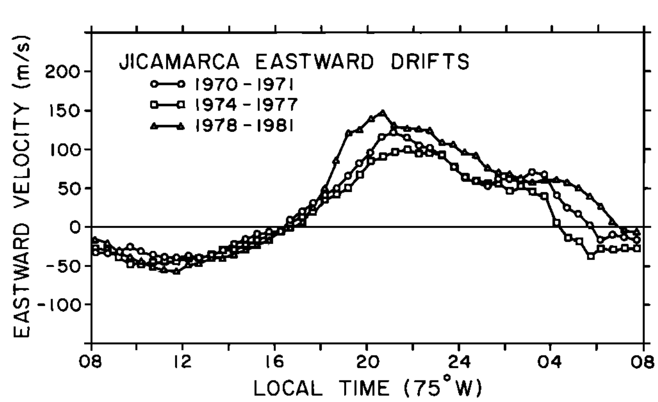

Fig. 2. *F* region average zonal plasma drifts during the solar maximum periods of 1970–1971 and 1978–1981, and the 1974–1977 period of solar minimum. The 1978–1981 period was considerably more active than the other two.

netic activity. The seasonal averages of the 1978–1981 east-west drifts, not shown here, support this conclusion. In particular, the higher altitude of the *F* region peak during summer and equinox does not seem to be associated with larger east-west drifts. This conclusion is also in agreement with the results obtained during the Condor campaign in March 1983 (M. C. Kelley et al., unpublished manuscript, 1985), when the comparison of two nights of radar interferometer data showed larger east-west drift velocities on the night when the *F* peak was lower. This suggests that other parameters determine the day to day variations of the plasma drifts.

Comparison With Other Drift Measurements

F region east-west drifts have been measured at night, during periods of equatorial spread *F*, for a number of years using the spaced receiver scintillation technique at Ancon, Peru. Figure 3 compares the average Jicamarca nighttime drifts to corresponding spaced receiver scintillation drift data [*MacKenzie and Basu*, 1982]. The evening drifts measured with the spaced receiver technique are consistently larger than the average drifts measured with the incoherent scatter technique, especially during solar minimum. Correcting "apparent" drifts to "true" drifts might reduce the scintillation drifts by 20% or so [*Wernik et al.*, 1983], but the difference would still be large. Other spaced receiver observations using VHF polarimeters in the Brazilian low latitude region during 1981–1982 indicated maximum average plasma drifts of about 250 m/s [*Abdu et al.*, 1985], which is even larger than the velocities measured at Ancon.

The spaced receiver scintillation and polarimeter drifts can only be made during periods of equatorial spread *F*. It perhaps could be argued that, during these occasions, the east-west drifts are somewhat larger due to larger neutral winds caused by reduced ion drag [*Sipler et al.*, 1983]. However, even though radar interferometer measurements (which can only be made when spread *F* is present) at Jicamarca do indeed show large and rapid variations in the *F* region east-west plasma drifts, after averaging out these variations the velocities are in good agreement with the incoherent scatter

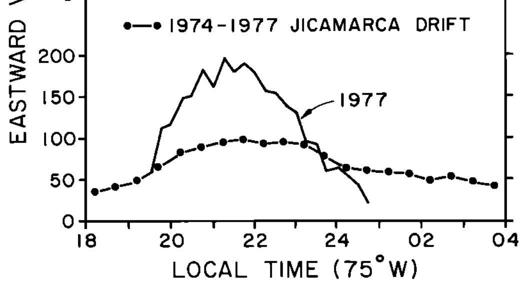

Fig. 3. Comparison between Jicamarca incoherent scatter drifts and spaced receiver scintillation drifts measured at Ancon, Peru. Each scintillation drift curve is the average of about 9 nights.

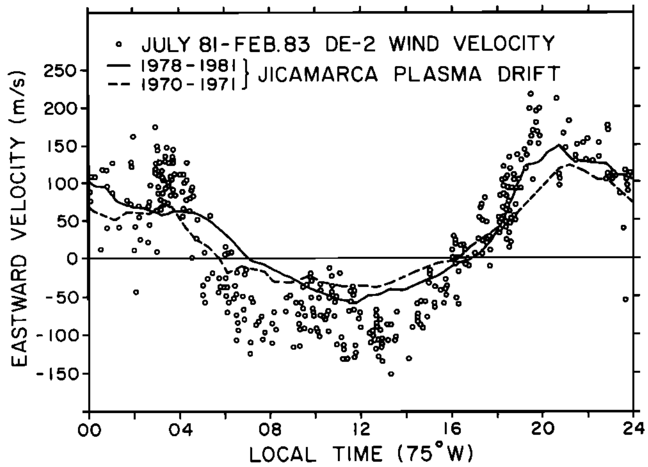

Fig. 4. Comparison of the Jicamarca average drifts with the DE-2 wind data published by *Wharton et al.* [1984].

data. Therefore, at present, we have no explanation for the discrepancy between the radar and spaced receiver data.

Figure 4 shows a comparison of the Jicamarca average drifts with the east-west wind measurements from the DE-2 satellite published by *Wharton et al.* [1984]. As expected, the nighttime plasma drifts are somewhat smaller than the *F* region neutral winds which drive the plasma via the *F* region dynamo field. A more detailed DE-2/Jicamarca comparison is given by *Herrero et al.* [1985]. On the other hand, the Jicamarca east-west drifts are usually somewhat higher than the nighttime neutral wind velocities measured with Fabry-Perot interferometers [*Sipler and Biondi*, 1978; *Sipler et al.*, 1983] and from the motion of 630.0 nm nightglow depletions observed during similar solar conditions [*Weber et al.*, 1978; *Carman*, 1983; *Sobral et al.*, 1985]. The differences are probably due mainly to the differences in height for the three measurements. The incoherent scatter and DE-2 measurements describe the local drifts at the *F* region peak or above, whereas the airglow emission is from the lower edge of the *F* region. The daytime plasma drifts are considerably smaller than the *F* region neutral winds, which is in agreement with theory, since during the day the east-west plasma drifts are strongly coupled to the *E* region winds at slightly higher latitudes, due to the high *E* region conductivity [*Woodman*, 1972].

Recently, J. W. Meriwether et al. (unpublished manuscript, 1985) have studied in detail the nighttime equatorial zonal and meridional winds with a Fabry-Perot interferometer in Arequipa, Peru (16.5°S, 71.4°W, geographic; magnetic dip 5°S). They observed zonal neutral wind velocities comparable to the Jicamarca plasma drifts but with considerably larger seasonal variations. These data also show large day to day variations and suggest a decrease of the zonal wind speeds during geomagnetically active periods.

Height and Time Variations of the
F Region East-West Drifts

The daytime and nighttime *F* region east-west drifts measured at Jicamarca sometimes show large fluctuations in time scales of 5–10 min, as shown in Figure 5. However, the average profiles obtained with integration times of 20–30 min usually vary only slowly with time and do not change much with height except at nighttime when there is a shear below the *F* region peak. These high time resolution results should

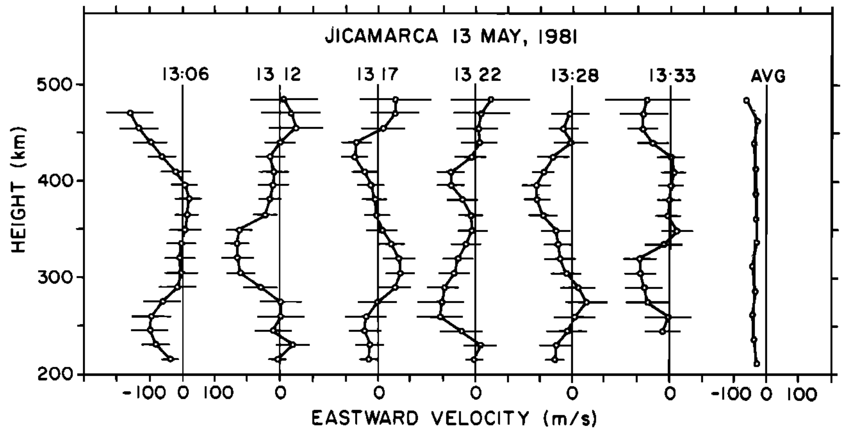

Fig. 5*a*

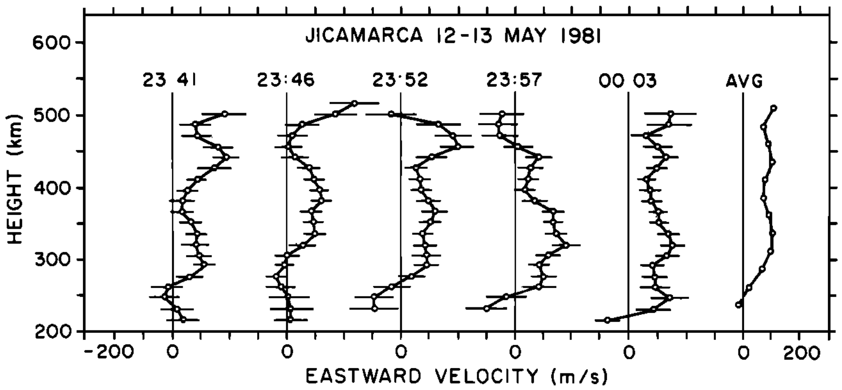

Fig. 5*b*

Fig. 5. (*a*) Examples of highly variable profiles of the east-west plasma drifts measured with an integration time of about 5 min during daytime. (*b*) Same as Figure 5*a* but for nighttime.

probably be treated with caution, however, since the measurement and data analysis procedures used were not optimized for the detection of wavelike perturbations like shown in Figure 5. These apparent perturbations in the east-west drift actually could be due partly to spatial fluctuations in the vertical drift, because of the height dependent horizontal spacing of the two antenna beams. The Jicamarca east-west drifts are obtained essentially by dividing the difference between the two line of sight drifts by sin 6.78°. Fluctuations in the vertical velocity with periods of about one half of the integration time (5 min) and wavelengths of one half the horizontal separation in the *F* region of the scattering volumes (about 40–100 km) will modulate strongly the apparent height profiles of the east-west drifts. The height profiles of the vertical drifts do, in fact, also show occasional fluctuations, but with considerably smaller amplitudes. The source of these wavelike perturbations cannot be determined without further investigation and so we will not discuss the topic further here. In any case, when the drift data are averaged over a height range of 100 km, these fluctuations are largely eliminated.

The average profiles obtained with integration times of 20 min or longer are usually height independent near the *F* region peak and above, as was first inferred from early east-west drift measurements at Jicamarca [*Woodman*, 1972], but some shear is present even at these heights at times. For example, Figure 6 shows a series of profiles measured with an integration time of about 32 min during the evening reversal period. No reliable drifts could be obtained at the lowest altitudes shortly after sunset due to the reduced electron densities. The reversal of the zonal drifts occurred initially at the higher altitudes, and a small shear developed at about 1700 LT. Figure 7 shows a few additional profiles on the same day. The east-west drift velocities were essentially independent of altitude above the *F* region peak. Similar results were observed at later local times and during other days.

Drift measurements below h_{max} in the *F* region valley at nighttime often show a pronounced shear in the east-west plasma drift, with westward velocities at the lowest altitudes reversing to eastward at higher altitudes [*Valenzuela et al.*, 1980; *Kudeki et al.*, 1981]. Figure 8 shows examples of this shear obtained by averaging the incoherent scatter drifts for about 20 min. Here h_m denotes the height of maximum backscattered power and should be close to h_{max}. Spread *F* echoes appeared shortly after 1947 at the lower altitudes, making the drift measurements unreliable below about 300 km. During other nights these shears, which seem to be a permanent feature of the nighttime equatorial ionosphere, were observed to occur at least up to about 0100 local time. Their detection with the incoherent scatter observations is difficult, however, since they occur in regions of reduced electron density, except during summer, when large prereversal enhancements of the upward drift move the layer to high altitudes, when there is still sufficient ionization at the lower altitudes, due to the late occurrence of the *E* region sunset, to permit measurements.

As mentioned above, during periods of equatorial spread *F*, radar interferometer observations made at Jicamarca can be

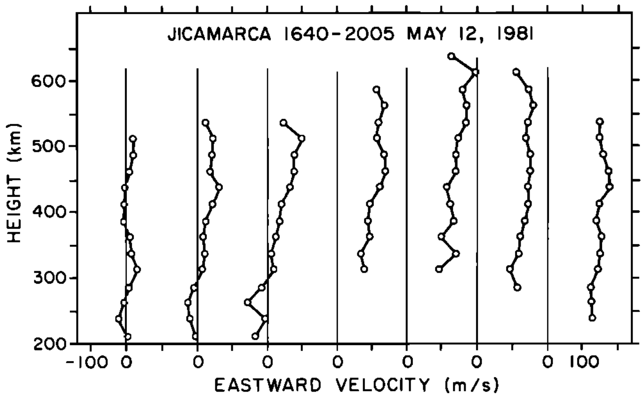

Fig. 6. Height profiles of the Jicamarca incoherent scatter drifts, obtained with an integration time of about 32 min, near the evening reversal time.

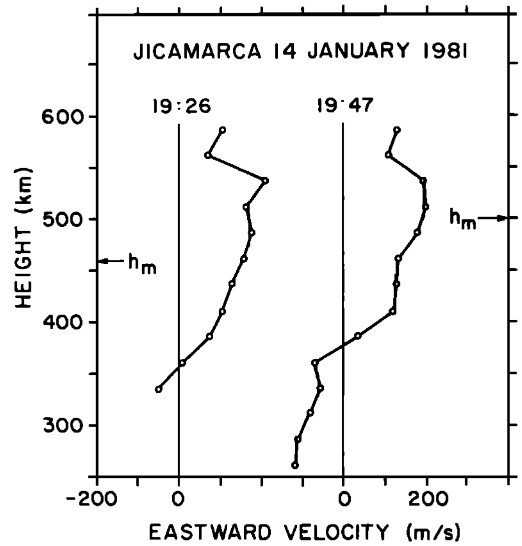

Fig. 8. Examples of the shear in the east-west drift measured with the incoherent scatter technique. Here h_m denotes the height of maximum backscattered power.

used to measure the zonal drifts of the irregularities. These measurements give average drifts in good agreement the incoherent scatter drifts. Figure 9 shows a particularly nice example of such interferometer drift data extending over a large range of altitudes. In this case, the height of the *F* region peak was above 600 km. The average drifts decrease slightly with altitude above about 600 km, whereas at lower altitudes there is a noticeable decrease of the eastward drift. During this time period, no drift measurements could be made below about 350 km, but it is likely that the eastward drift velocity continued decreasing below 400 km, and that westward velocities were present in the lower *F* region. Other radar interferometer observations show this type of variation whenever measurements can be made over a large range of altitudes. These interferometer measurements, which have considerably better temporal and spatial resolution than the incoherent scatter measurements, often show large and rapid fluctuations in the east-west drift of the irregularities.

THEORIES

Numerical models of the low latitude *F* region east-west drifts were developed by *Heelis et al.* [1974] and *Richmond et al.* [1976]. The first model used only a diurnal tidal mode but included the effect of *F* region polarization electric fields [e.g., *Rishbeth*, 1971], which are important at night. *Richmond et al.* [1976] used the diurnal tide modified by ion drag and the semidiurnal (2, 4) mode to obtain *F* region drifts in the upper *E* and lower *F* regions at low and middle latitudes. These models give zonal as well as vertical drifts. Figure 10 compares their predictions with Jicamarca data from 1970–1981, a period which corresponds to an average sunspot number of about 90. The drifts from Richmond et al. follow the experimental data fairly closely except for the evening-premidnight period when *F* region polarization electric fields, not taken into account in the model, are important. These polarization fields can also explain the evening prereversal enhancement of

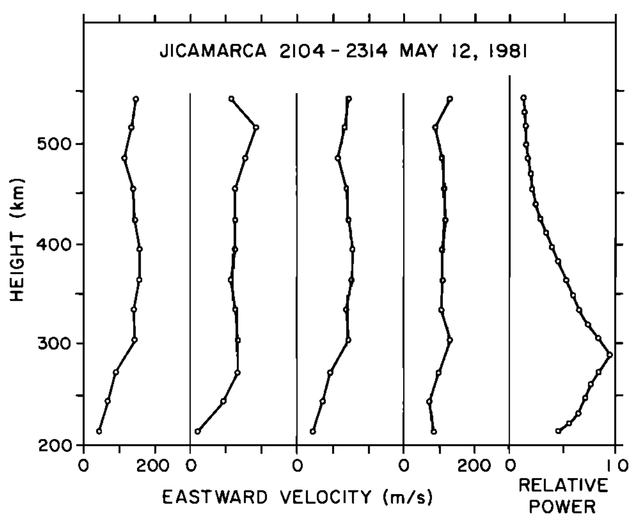

Fig. 7. Additional examples of height profiles of the zonal plasma drifts. The curve on the far right shows the backscatter power profile at about 2200 local time. The power profile multiplied by the height squared corresponds roughly to the electron density profile. This profile moved downward slowly during this period.

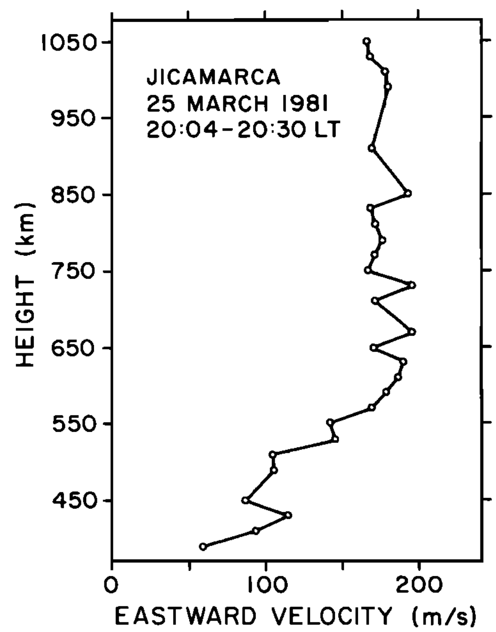

Fig. 9. Height profile of the east-west plasma drifts measured with the radar interferometer technique.

the vertical plasma drifts. The model of Heelis et al. is less satisfactory, with considerably larger eastward drifts near the F region peak in the premidnight sector and a later evening reversal time.

Heelis et al. [1974] also modeled the height variation of the east-west drifts. Their results show large shears in the zonal drifts at 2300 and 2400 local time, with the eastward drifts decreasing slowly with altitude above the F region peak, and westward drifts at the lower altitudes. These profiles have the same height variation as the Jicamarca data at somewhat earlier local times but have maximum eastward velocities of about 300 m/s (near the F region peak), which is much larger than our average value. *Zalesak et al.* [1982] suggested that the westward tilt of equatorial F region plasma plumes was due to the occurrence of a large shear in the zonal plasma drifts above the F region electron density peak which is in contradiction to the height profiles of the plasma drifts shown above. Recently, the height variation of zonal plasma drifts was also studied by *Anderson and Mendillo* [1983] and by *Takeda and Maeda* [1983]. The first of these studies assumed that the east-west plasma drift is given by

$$V_i = \int \sigma_p U B \, ds / B \int \sigma_p \, ds \quad (1)$$

where σ_p is the Pedersen conductivity, U is the zonal wind, B is the magnetic field strength, and the integrations are performed from one end of the field line to the other. The wind model used in the calculations was based on the Fabry-Perot interferometer measurements at Kwajalein [*Sipler et al.*, 1983] and on theoretically calculated low latitude thermospheric winds. Figure 11 shows the drift velocity profiles obtained at 1900 local time, with and without assuming a cosine latitudinal variation of the zonal neutral winds. For curve a the wind velocity at the equator is twice as large as the velocities at $\pm 15°$ dip latitude, but for curve b there is no latitudinal variation. The decrease of the wind velocity with latitude follows the results from the thermospheric model calculations of *Anderson and Roble* [1974]. Comparing Figures 9 and 11, we can see that the height variation of the Jicamarca data suggests that the wind speed decreases at least somewhat with latitude. The satellite results from DE-2 also suggest a decrease of the wind speed with latitude [*Wharton et al.*, 1984]. The maximum drift velocity from this model increases up to about 2100 local time when the wind speed is maximum. Figure 11 was

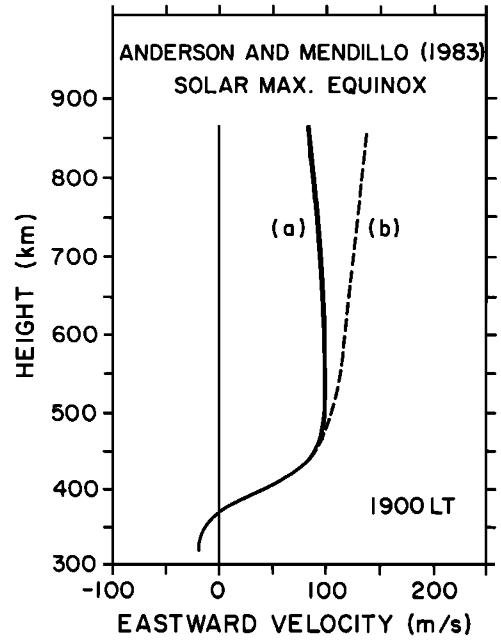

Fig. 11. Height variation of the equatorial zonal drifts obtained with and without assuming a latitudinal variation of the F region winds (curves a and b, respectively).

calculated assuming a prereversal maximum vertical drift of about 25 m/s. A higher upward drift, typical of the equinoctial months during the 1978–1981 period, would move the profile to higher altitudes.

Numerical model calculations of the equatorial currents and electric fields at 1800 local time for sunspot numbers of 100 and 280, including the effect of the **J** × **B** force which modifies the atmospheric tidal modes, were recently published by *Takeda and Maeda* [1983]. They have also calculated the vertical electric field from 90 to 600 km. This electric field drives the equatorial electrojet in the E region, and the east-west plasma drifts in the F region. The calculations show a reversal of the field at about 150 km, with downward electric fields (which cause eastward drifts) at the higher altitudes. Near the F region peak and above the drifts are essentially height independent. The shape of the electric field profile and the calculated magnitudes are in good agreement with our experimental values. The height of the shear region is lower than observed, but this is due to the fairly small upward velocity of 16 m/s (more than a factor of two smaller than observed in the last solar maximum) used as an input in the calculations. This model also explains that the anomaly in magnetic declination observed by the MAGSAT satellite on the duskside near the dip equator [*Maeda et al.*, 1982] is a result of the equatorial meridional current system.

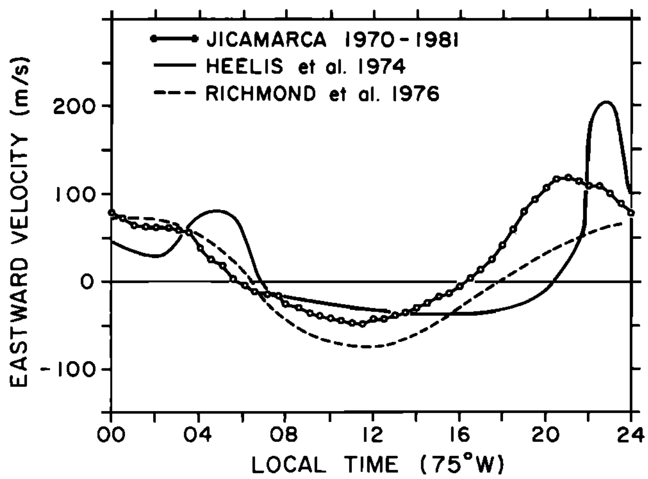

Fig. 10. Comparison between the zonal drifts measured at Jicamarca for an average sunspot number of 90 and the results from two numerical models.

CONCLUSIONS

The Jicamarca data reported here show an increase in the nighttime eastward drifts with solar activity as characterized by the sunspot number or by the 10.7 cm flux. The maximum evening eastward drift changed from about 105 to 150 m/s between 1974–1977 and 1978–1981, as the solar sunspot number increased from an average of 25 to about 170. There is considerable day to day variation in the magnitude of the nighttime drifts, but there is no apparent variation with season and geomagnetic activity. This last result is in contrast with the significant changes frequently observed in the vertical drifts (i.e., east-west electric fields) during magnetically disturbed periods [e.g., *Gonzales et al.*, 1979; *Fejer*, 1981].

The incoherent scatter drifts are consistently smaller than the spaced receiver scintillation drifts measured at Ancon during identical periods of the solar cycle. This disagreement was largest during the solar minimum period. Spaced receiver polarization measurements in the Brazilian low latitude region give even larger nighttime eastward drifts. This disagreement is apparently not due to the presence of spread *F* irregularities (used as tracers of the plasma motion in the spaced receiver measurements), since the Jicamarca incoherent scatter and radar interferometer drifts seem to be in good agreement. In addition, the height profiles of the zonal drifts observed at Jicamarca indicate that this disagreement cannot be explained as being due to a difference in altitudes probed by the two techniques.

The zonal plasma drifts do not show any large altitudinal variation on time scales of 20–30 min during the day. The evening-premidnight observations indicate westward drifts well below the *F* peak and eastward drifts at higher altitudes. The shear region is not easily probed with the incoherent scatter technique due to the reduced electron densities there. Above the *F* region peak the nighttime eastward drifts change little with altitude, in agreement with recent numerical models developed by *Anderson and Mendillo* [1983] and by *Takeda and Maeda* [1983]. The comparison between the Jicamarca drifts and the drifts from numerical models of the low latitude ionosphere show the importance of *F* region polarization electric fields in the sunset-premidnight period.

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REFERENCES

Abdu, M. A., I. J. Kantor, I. S. Batista, and E. R. Paula, East-west plasma bubble irregularity motion determined from spaced VHF polarimeters: Implications on velocity shear in the zonal *F* region bulk plasma motion, *Radio Sci.*, *20*, 111, 1985.

Anderson, D. N., and M. Mendillo, Ionospheric conditions affecting the evolution of equatorial plasma depletions, *Geophys. Res. Lett.*, *10*, 541, 1983.

Anderson, D. N., and R. G. Roble, The effect of vertical $E \times B$ ionospheric drifts on *F* region neutral winds in the low-latitude thermosphere, *J. Geophys. Res.*, *79*, 5231, 1974.

Basu, S., J. P. McClure, S. Basu, W. B. Hanson, and J. Aarons, Coordinated study of equatorial scintillation and in situ and radar observations of nighttime *F* region irregularities, *J. Geophys. Res.*, *85*, 5119, 1980.

Carman, E. H., Equatorial depletions in the 630.0 nm airglow at Vanimo, *Planet. Space Sci.*, *31*, 355, 1983.

Chandra, H., R. K. Misra, M. R. Deshpande, and R. G. Rastogi, Ionospheric irregularities and their drifts at Thumba during 1964–1968, *Indian J. Pure Appl. Phys.*, *8*, 548, 1970.

Farley, D. T., H. M. Ierkic, and B. G. Fejer, Radar interferometery: A new technique for studying plasma turbulence in the ionosphere, *J. Geophys. Res.*, *86*, 1467, 1981.

Fejer, B. G., The equatorial ionospheric electric fields: A review, *J. Atmos. Terr. Phys.*, *43*, 377, 1981.

Fejer, B. G., D. T. Farley, C. A. Gonzales, R. F. Woodman, and C. Calderon, *F* region east-west drifts at Jicamarca, *J. Geophys. Res.*, *86*, 215, 1981.

Gonzales, C. A., M. C. Kelley, B. G. Fejer, J. F. Vickrey, and R. F. Woodman, Equatorial electric fields during magnetically disturbed conditions: Implications of simultaneous auroral and equatorial measurements, *J. Geophys. Res.*, *84*, 5803, 1979.

Heelis, R. A., P. C. Kendall, R. J. Moffet, D. W. Windle, and H. Rishbeth, Electrical coupling of the *E* and *F* regions and its effect on *F*-region drifts and winds, *Planet. Space Sci.*, *21*, 743, 1974.

Herrero, F. A., H. G. Mayr, N. W. Spencer, A. E. Hedin, and B. G. Fejer, Interaction of zonal winds with the equatorial midnight pressure bulge in the earth's thermosphere: Empirical check of momentum balance, *Geophys. Res. Lett.*, *12*, 491, 1985.

Kudeki, E., B. G. Fejer, D. T. Farley, and H. M. Ierkic, Interferometer studies of equatorial *F* region irregularities and drifts, *Geophys. Res. Lett.*, *8*, 377, 1981.

MacKenzie, E., and S. Basu, Variation of equatorial *F*-region irregularity parameters as a function of solar activity, *Rep. AFGL TR-82-0369*, Air Force Geophys. Lab., Bedford, Mass., 1982.

Maeda, H., T. Iyemori, T. Araki, and T. Kamei, New evidence of a meridional current system in the equatorial ionosphere, *Geophys. Res. Lett.*, *9*, 337, 1982.

Rastogi, R. G., H. Chandra, and R. K. Misra, Features of the ionospheric drifts over the magnetic equator, *Space Res.*, *12*, 984, 1972.

Richmond, A. D., S. Matsushita, and J. D. Tarpley, On the production mechanism of electric currents and fields in the ionosphere, *J. Geophys. Res.*, *81*, 547, 1976.

Rishbeth, H., The *F*-region dynamo, *Planet. Space Sci.*, *19*, 263, 1971.

Sipler, D. P., and M. A. Biondi, Equatorial *F*-region neutral winds from nightglow OI 630.0 nm Doppler shifts, *Geophys. Res. Lett.*, *5*, 373, 1978.

Sipler, D. P., M. A. Biondi, and R. G. Roble, *F*-region neutral winds and temperatures at equatorial latitudes: Measured and predicted behaviour during geomagnetically quiet conditions, *Planet. Space Sci.*, *31*, 53, 1983.

Sobral, J. H. A., M. A. Abdu, and Y. Sahai, Equatorial plasma bubble eastward velocity characteristics from scanning airglow photometer measurements over Cachoeira Paulista, *J. Atmos. Terr. Phys.*, in press, 1985.

Takeda, M., and H. Maeda, *F*-region dynamo in the evening—Interpretation of equatorial ΔD anomaly found by MAGSAT, *J. Atmos. Terr. Phys.*, *45*, 401, 1983.

Valenzuela, A., G. Haerendel, A. Foppl, E. Rieger, B. G. Fejer, and M. C. Kelley, Incoherent scatter radar and barium cloud measurements of electric fields in the equatorial zone (abstract), *Eos Trans. AGU*, *61*, 315, 1980.

Weber, E. J., J. Buchau, R. H. Eather, and S. B. Mende, North-south aligned equatorial airglow depletions, *J. Geophys. Res.*, *83*, 712, 1978.

Wernik, A. W., C. H. Liu, and K. C. Yeh, Modeling of spaced-receiver scintillation measurements, *Radio Sci.*, *18*, 743, 1983.

Wharton, L. E., N. W. Spencer, and H. C. Mayr, The earth's thermospheric superrotation from Dynamics Explorer 2, *Geophys. Res. Lett.*, *11*, 531, 1984.

Woodman, R. F. East-west ionospheric drifts at the magnetic equator, *Space Res.*, *12*, 969, 1972.

Yeh, K. C., J. P. Mullen, J. R. Medeiros, R. F. da Silva, and R. T. Medeiros, Ionospheric scintillation observations at Natal, *J. Geophys. Res.*, *86*, 7527, 1981.

Zalesak, S. T., S. L. Ossakow, and P. K. Chaturvedi, Nonlinear equatorial spread *F*: The effect of neutral winds and background Pedersen conductivity, *J. Geophys. Res.*, *87*, 151, 1982.

D. T. Farley and B. G. Fejer, School of Electrical Engineering, Cornell University, Ithaca, NY 14853.

E. Kudeki, Department of Electrical and Computer Engineering, University of Illinois, Urbana, IL 61801.

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