January 1, 1993

F-region plasma drifts over Arecibo: Solar cycle, seasonal and magnetic activityeffects

Bela G. Fejer, *Utah State University*

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 98, NO. A8, PAGES 13,645–13,652, AUGUST 1, 1993

F Region Plasma Drifts Over Arecibo: Solar Cycle, Seasonal, and Magnetic Activity Effects

B. G. FEJER

Center for Atmospheric and Space Sciences, Utah State University, Logan

We have used Arecibo incoherent scatter measurements from 1981 to 1990 to determine the characteristics of low-latitude F region plasma drifts. The measurements show large day-to-day variability even during magnetically quiet periods. The average poleward/perpendicular plasma drifts do not change significantly with season and solar cycle except in the midnight-morning sector. The zonal drifts show clear solar cycle and seasonal effects. The afternoon-nighttime eastward drifts increase with solar flux; the westward drifts in the early morning-afternoon sector show a large increase from summer to winter but are independent of solar activity. The two perpendicular velocity components also respond differently to magnetic activity. The average northward/perpendicular drifts decrease with magnetic activity during the day but do not exhibit a systematic response at night. The zonal component shows increased westward drifts occurring predominantly at night. The plasma drifts along the magnetic field lines exhibit large altitudinal and seasonal variations, particularly near solar minimum, and are generally anticorrelated with the perpendicular/north drifts. The drift patterns observed by the Arecibo and the middle and upper atmosphere radars have significantly different seasonal dependence. This can be explained by electrodynamic effects in the corresponding local and conjugate ionospheres. The large longitudinal variation of the quiet time F region plasma drifts results from the displacement between the geographic and dip equators and from magnetic field declination effects. In general, the longitudinal variation should also depend on magnetic activity.

1. Introduction

The dynamics of the ionosphere are controlled by a number of coupled processes involving ionization production and loss, electrodynamic plasma drifts, thermospheric neutral winds, and diffusion. A comprehensive review of ionospheric and thermospheric processes was presented by *Kelley* [1989]. Radar and satellite measurements have been used to determine the characteristics of plasma drifts at F region heights, where transport processes are particularly important. In this region, the plasma drifts perpendicular to the earth's magnetic field are related to the ionospheric electric field by $\mathbf{V} = \mathbf{E} \times \mathbf{B}/B^2$. *Richmond et al.* [1980] have presented an empirical model of quiet time solar minimum ionospheric electrodynamic plasma drifts (electric fields) at middle and low latitudes based on incoherent scatter radar measurements in the American and European sectors.

Ionospheric plasma drifts measured from the Arecibo Observatory (18°N, 67°W; magnetic latitude, 30°N) have been used in several studies of low-latitude electrodynamics [e.g., *Behnke and Harper*, 1973; *Behnke and Hagfors*, 1974; *Rishbeth et al.*, 1978; *Burnside et al.*, 1983*b*, 1991*b*; *Ganguly et al.*, 1987; *Berkey et al.*, 1990]. Radar observations at Arecibo have also been used to determine the response of low-latitude electric fields to large changes in the high-latitude current system [e.g., *Gonzales et al.*, 1983; *Fejer et al.*, 1990]. The current understanding of the low-latitude plasma drifts was reviewed by *Fejer* [1991]. In spite of the large number of these studies, however, at present there is no empirical model of the Arecibo drifts valid for different solar activity and geomagnetic conditions.

Middle- to low-latitude F region plasma drift measurements have also been made over the last few years with the middle and upper atmosphere (MU) radar at Shigaraki (34.9°N, 136.1°E; magnetic latitude, 29.3°N), Japan [*Oliver et al.*, 1988; *Fukao et al.*, 1991; W. L. Oliver, Y. Yamamoto, T. Takami, S. Fukao, M. Yamamoto, and T. Tsuda, Middle and upper radar observations of ionospheric electric fields, submitted to *Journal of Geophysical Research*, 1993] (hereafter referred to as Oliver et al., 1993). This radar samples the ionosphere at essentially the same magnetic latitude as the Arecibo radar but at a considerably higher geographical latitude. *Fejer* [1991] compared the initial F region drift measurements from the MU radar [*Oliver et al.*, 1988] with the Arecibo solar minimum results of *Ganguly et al.* [1987]. Oliver et al. (1993) used a large set of observations to examine the dependence of the F region MU radar drifts on season and solar cycle. *Heelis and Coley* [1992] have studied the latitudinal variation of the longitudinally averaged low- and mid-latitude zonal plasma drifts measured by the ion drift meter on board the polar orbiting Dynamics Explorer 2 (DE 2) satellite. They showed that the DE 2 data measured at 30° magnetic latitude are in closer agreement with the MU radar drifts of *Fukao et al.* [1991] than with the Arecibo solar minimum results of *Ganguly et al.* [1987]. Seasonal and solar cycle effects on the F region plasma drifts over Millstone Hill (42.6°N, 71.5°W; magnetic latitude, 54°N) were studied by *Buonsanto et al.* [1993].

In the last few years, extensive ionospheric plasma drift measurements have become available through the National Center for Atmospheric Research (NCAR) Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) incoherent scatter radar data base. We use the 1981-1986 Arecibo plasma drifts from the data base and also additional measurements from 1986 to 1990 to obtain initially an empirical model for the average Arecibo F region plasma drifts perpendicular and parallel to the Earth's magnetic field during both magnetically quiet and disturbed conditions. This work extends previous studies of the Arecibo F region drifts by *Richmond et al.* [1980], *Ganguly et al.* [1987], *Berkey et al.* [1990], and *Fejer* [1991]. We also compare the average Arecibo drifts with recent results from the MU radar (Oliver et al., 1993) and with zonal plasma drifts measured by the DE 2 satellite [*Heelis and Coley*, 1992]. Our results indicate substantial longitudinal dependence of the mid- to low-latitude zonal plasma drifts.

Paper number 93JA00953.
0148-0227/93/93JA-00953$05.00

2. Measurement Techniques and Data Analysis

The initial measurements of ionospheric plasma drifts with the Arecibo incoherent scatter radar were reported by *Behnke* [1971]. The characteristics of the average ionospheric electric fields over Arecibo during the 1974-1977 solar minimum period were determined by *Ganguly et al.* [1987]. In this case, the zonal and north-south components of the plasma drift in the plane perpendicular to the ambient magnetic field were obtained from measurements at three fixed positions with a time resolution of about an hour. The drift measurements were changed in 1981 from a three-position mode to a continuously scanning mode over 360° in azimuth at a fixed elevation of about 75°, with a cycle period of about 16 min. Typically, about 12 line-of-sight velocity measurements are made in each 360° azimuthal scan. Data from 19 range gates above 160 km were obtained until October 1985, and data from 13 gates were obtained thereafter.

The line-of-sight measurements need to be corrected for instrumental offsets of the order of 10-20 m/s associated with the transmitter "chirp" resulting from a small phase shift during transmission of the radar pulse. This frequency shift has no effect on the horizontal components of the drift velocity (e.g., zonal drift), since they are obtained by taking the difference of line-of-sight measurements, but it must be taken into account in determining the drift parallel to the geomagnetic field and the upward/northward drift in the plane perpendicular to the magnetic field. The procedure used to remove this and other bias effects from the 1981-1986 Arecibo drift measurements in the NCAR CEDAR data base consisted in solving the one-dimensional electron density continuity equation in the topside ionosphere [*Berkey et al.*, 1990]. Since May 1985, the Arecibo measurements have used a multifrequency technique [*Sulzer*, 1986] which results in a significant reduction of the statistical error when the signal-to-noise ratio is much larger than 1, as is usually the case during the day near the F region peak. This technique should also provide for an on-line correction for the chirp. The analysis procedure used to determine the velocity components on the NCAR incoherent scatter data base is described in *Berkey et al.* [1990]. This analysis neglects horizontal velocity gradients. The components perpendicular to the geomagnetic field are assumed to be height independent, whereas the parallel component is allowed to change with altitude. The simultaneous fitting of all heights minimizes the scatter and the error in the fitted velocity components.

We have studied Arecibo drifts from the NCAR data base for the period of January 1981 through August 1986. The more recent Arecibo drifts in the data base consist only of line-of-sight velocities which have the automatic chirp correction. The average velocities obtained from the 1981-1986 CEDAR data base are in good agreement with the corresponding 1974-1977 average drifts of *Ganguly et al.* [1987] and also with results from earlier measurements [e.g., *Behnke and Harper*, 1973], which used different data-taking and analysis procedures. The 1974-1977 data will not be used in our study, however, since they have no error bars and are noisier than the more recent measurements. The drift velocities after August 1986 were obtained directly from the Arecibo Observatory, where a different data analysis was used. These data, which have been used by *Burnside et al.* [1991*b*], correspond to an altitude of 300 km. Average velocities for different geophysical conditions (season, solar cycle, magnetic activity) were also determined for this data set. We observed that there is good agreement between the results from the NCAR data base and from the 1986-1990 data for the zonal velocities but not for the perpendicular/north and parallel components, especially during winter solar minimum conditions. We believe that these discrepancies result in part from problems with some of the newer data. As a result of this inconsistency, we have decided to use only the data from the NCAR data base for the study of the northward/perpendicular and parallel drifts. These data consist of 120 days of observations. Since there is no problem with the zonal drifts, we have used 169 days of World Day observations during 1981-1990 for the study of this velocity component.

3. Results

The Arecibo F region plasma drifts show significant day-to-day variability even during extended geomagnetically quiet periods. Figure 1 illustrates the variability of the northward/perpendicular ($V_{\perp N}$) and eastward ($V_{\perp E}$) plasma drifts during low solar activity (Sa < 120, where Sa is the decimetric solar flux index), magnetically quiet conditions. In this study, local time (LT) corresponds to Arecibo standard time (AST = UT - 4 h). Over Arecibo, an upward/poleward (eastward) plasma drift of 27 m/s corresponds to an eastward (southward) electric field of about 1 mV/m. The scatter on the data is usually larger than the error in the measurements (about 10 m/s).

In the following sections we will focus on the characteristics of the seasonally averaged drifts. The results to be presented were obtained by averaging the velocity measurements in half-hour bins and then performing three-point running averages.

Perpendicular/Northward Drifts

Figure 2 shows the F region quiet time average upward/northward drifts for two levels of the 10.7-cm solar flux index during June solstice (May-August), equinox (March-April, September-October), and December solstice (November-February). The daytime drifts are generally upward/poleward from about sunrise to early afternoon, with maximum values of about 20 m/s. The morning (afternoon) reversal time occurs earliest during the June (December) solstice. The late-afternoon to midnight drifts are generally equatorward and have small amplitudes (less than about 10 m/s). There is no clear dependence of these drifts on solar activity except for the midnight-dawn period, when the northward drifts are largest during solar minimum winter months and smallest during the summer. The small differences in the times of velocity maxima and of reversals are not significant because of the large variability of the data (see Figure 1). The drifts shown in Figure 2 are in good agreement with previous observations [*Behnke and Harper*, 1973; *Behnke and Hagfors*, 1974] and with the 1974-1977 solar minimum average patterns reported by *Ganguly et al.* [1987]. The seasonal averages for solar maximum conditions have not been presented elsewhere, but these results are consistent with the 1981-1982 solar maximum average published by *Berkey et al.* [1990]. This agreement is expected, since both studies have used Arecibo drifts from the NCAR data base. Recently, *Burnside et al.* [1991*b*] reported the average values of a number of F region parameters measured at an altitude of 300 km over Arecibo during 14 World Day campaigns from October 1985 through October 1989. Their results for the perpendicular/north ion (and also for the

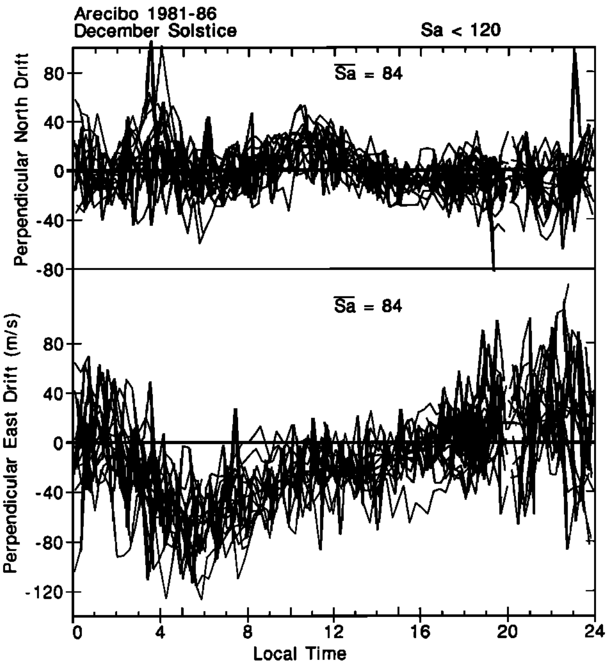

Fig. 1. Scatter plots of the perpendicular/north and east components of the Arecibo F region plasma drifts during magnetically quiet (Kp ≤ 3) and solar low decimetric flux (Sa < 120) conditions.

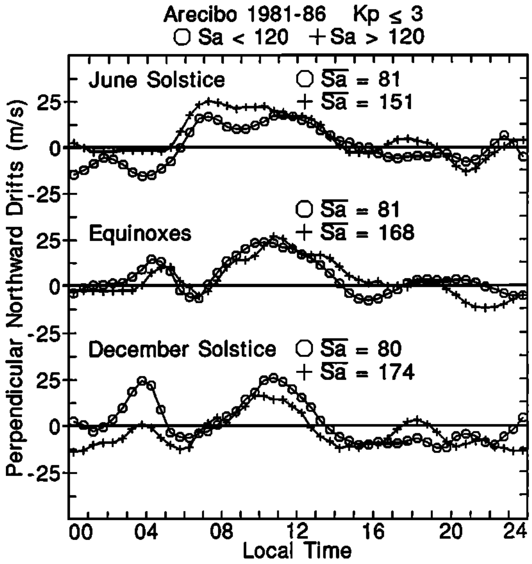

Fig. 2. Seasonal variation of the 1981-1986 average quiet time perpendicular/northward plasma drifts over Arecibo for two ranges of solar flux. The average values of the solar decimetric index are also shown.

parallel) drifts are generally in good agreement with our results for the equinox and the June solstice but not for the December solstice. We believe that these disagreements result in part from problems with some of their data.

Perpendicular/Eastward Drifts

The seasonal averages of the quiet time zonal drifts for two levels of solar activity are presented in Figure 3. The zonal drifts are westward from midnight to early afternoon and eastward in the afternoon-midnight sector. The afternoon

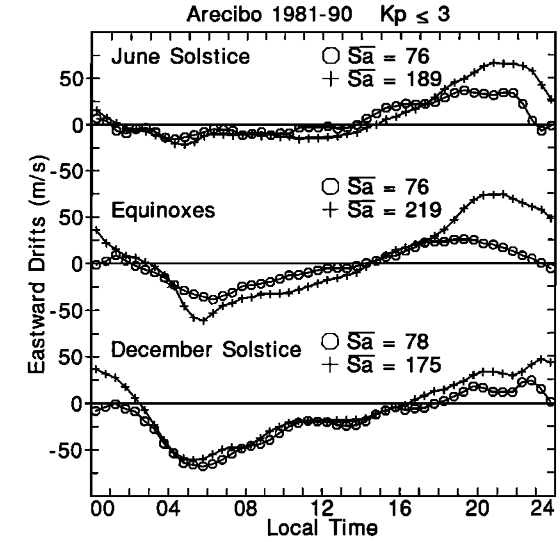

Fig. 3. Average quiet time zonal plasma drifts obtained from the 1981-1990 drift observations for Sa < 120 and Sa > 120.

reversal time occurs earliest (at about 1400 LT) during summer and latest (at about 1800 LT) during winter. The nighttime westward drifts are largest at about 0600 LT, with maximum values between 10 and 60 m/s during summer and winter, respectively. The maximum eastward drift occurs latest (about 2300-2400 LT) during the December solstice. The nighttime eastward drifts increase with solar activity, but the westward drifts remain unchanged. The solar minimum zonal drifts shown in Figure 3 resemble, in general, the average patterns presented by *Ganguly et al.* [1987], but our average westward drifts during summer and winter are smaller and larger, respectively. The increase of the evening eastward drifts is consistent with the results of *Berkey et al.* [1990] and also with equatorial zonal drift measurements [e.g., *Fejer et al.*, 1991]. We have also examined the bimonthly averages of the zonal drifts for the same ranges of solar activity. Our results indicate the absence of noticeable bimonthly variations within the 4-month seasonal periods considered here and also the good agreement of the March and September equinoctial averages.

Parallel Drifts

The drifts parallel to the magnetic field have a component related to the meridional neutral winds and a component driven by plasma diffusion [e.g., *Burnside et al.*, 1983*a*]. The neutral wind component is largely height independent, whereas the component due to plasma diffusion is related to the electron density height gradient. Figures 4 and 5 show the average parallel drifts (positive southward) over two height ranges for low and high solar fluxes, respectively. For the altitudinal ranges considered here, these drifts show largest height variations near dawn and dusk and for solar minimum. In the lower altitude range, the solar maximum drifts are essentially constant throughout the day. Several earlier studies [e.g., *Behnke*, 1971; *Behnke and Harper*, 1973] have pointed out that the parallel and perpendicular/north drifts are usually anticorrelated, since the plasma flow is largely horizontal. This relationship can be seen with the winter and equinoctial drifts but is not evident on the summer average data (see Figures 2, 4, and 5).

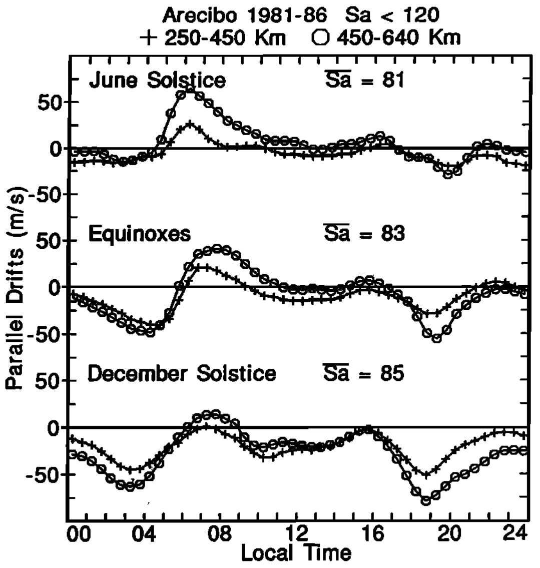

Fig. 4. Plasma drifts along the magnetic field averaged over two height ranges for low solar flux conditions.

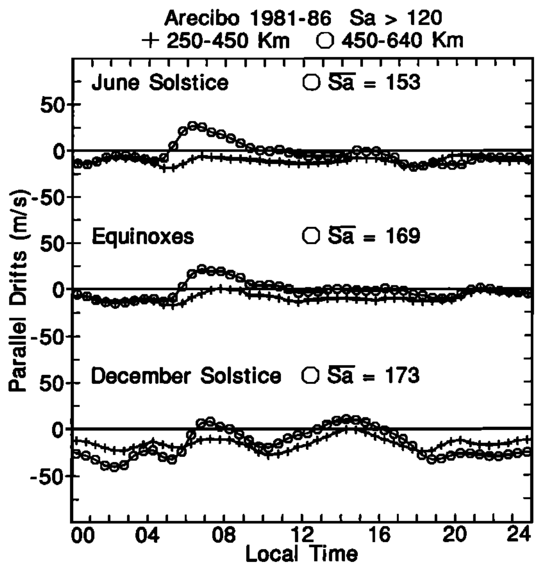

Fig. 5. Same as Figure 4 but for higher solar fluxes.

Magnetic Activity Effects

We have averaged the plasma drifts during magnetically quiet and disturbed conditions (defined by Kp ≤ 3 and Kp ≥ 4, respectively) for each season. For the northward/perpendicular drifts, however, we did not obtain statistically reliable averages during disturbed conditions for all seasons. As mentioned above, we have not used the parallel and perpendicular/north velocity measurements obtained after August 1986 because of problems with these data. Therefore, for this component we used a set of cubic splines [e.g., *Wand*, 1981] to calculate the yearly averaged drift patterns for Kp = 2 and Kp = 5 for a solar decimeteric index Sa = 120, which are presented in Figure 6. These data show that increased magnetic activity leads to smaller northward drifts during the day and slightly larger values near dusk. The smaller data set used by *Ganguly et al.* [1987] did not show noticeable magnetic activity effects on this velocity component. Figure 7 presents

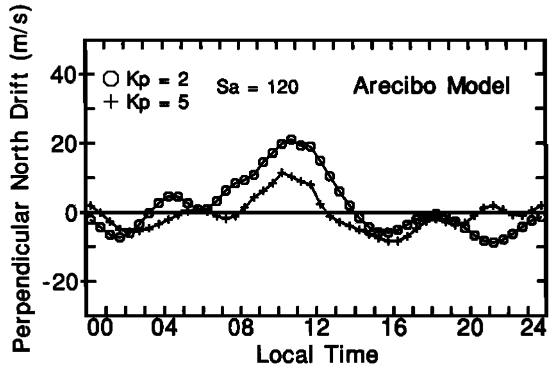

Fig. 6. Yearly average quiet and disturbed northward/perpendicular plasma drifts calculated for two values of Kp and for moderate solar flux conditions (Sa = 120).

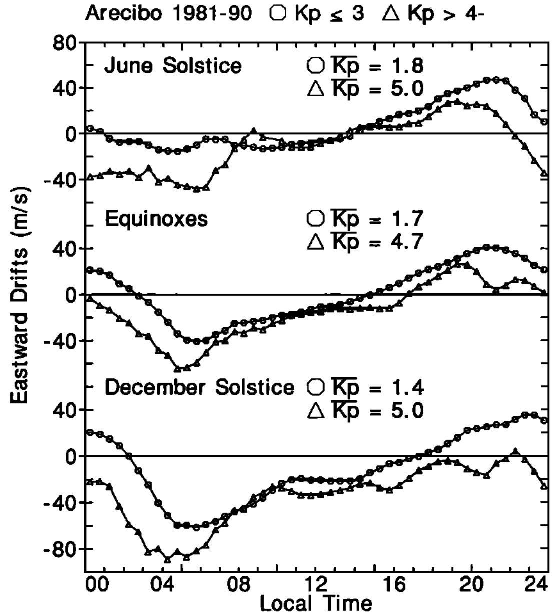

Fig. 7. Seasonal variations of the Arecibo quiet time and disturbed zonal plasma drifts.

the daily variations of the average zonal drifts during magnetically quiet and disturbed conditions. We can see that the disturbed westward velocity perturbations occur at all local times and have larger amplitudes at night than during the day. Our results indicate larger day-to-night asymmetry in the response of the zonal plasma drifts to magnetic activity than was reported by *Ganguly et al.* [1987]. Over Arecibo, large daytime westward drift perturbations are observed only during very disturbed (Kp ≥ 6) conditions [*Burnside et al.*, 1991*a*]. The implications of these results will be discussed later.

4. Comparison With Other Observations

Heelis and Coley [1992] used observations from the DE 2 satellite during the 1981-1983 period of high solar activity to determine the latitudinal variation of the low- to midlatitude zonal plasma drifts during magnetically quiet and disturbed conditions. The local time and seasonal coverage of this polar orbiting satellite were locked together with dawn and dusk measurements made during the solstices and with noon and midnight data obtained during the equinoxes. Figure 8 shows the local time distributions of the average quiet (Kp ≤ 2) and disturbed (Kp ≥ 3) zonal drifts within a 5° magnetic latitude

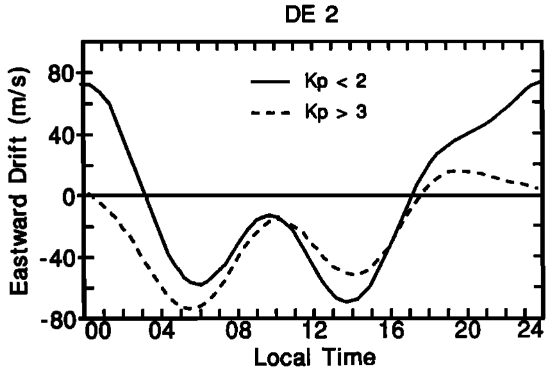

Fig. 8. Average zonal plasma drifts measured by the DE 2 satellite around 30° magnetic latitude during magnetically quiet (Kp < 3) and active (Kp > 3) periods [adapted from *Heelis and Coley*, 1992].

range centered at about 30°N (the approximate magnetic latitudes of the Arecibo and MU radars). The evening-morning quiet time DE 2 drifts are generally in good agreement with the equinox-winter solar maximum Arecibo data presented in Figure 3, but the satellite data show much larger westward drifts in the early afternoon sector. The radar and satellite disturbed drifts are also in good agreement except again for the 1000-1600 LT period.

MU radar observations have been recently used to study the morphology of low- to midlatitude F region plasma drifts [*Oliver et al.*, 1988; *Fukao et al.*, 1991; Oliver et al., 1993]. These measurements are usually made at 20° zenith angle using four beams pointed toward magnetic north, south, east and west. The typical time resolution is 45 min., and the range resolution is 38 km between 217 and 303 km. *Fejer* [1991] compared the initial measurements from the MU radar with solar minimum Arecibo data. This study showed good agreement on the peak-to-peak variations of both the perpendicular/north and east drifts. Oliver et al. (1993) used a large data set of MU radar observations to examine the variation of the F region drifts with season and solar cycle. They showed that the northward/perpendicular drifts do not change significantly with solar flux but that the evening and nighttime eastward drifts increase from solar minimum to maximum. These results are consistent with the solar cycle dependence observed at Arecibo. Oliver et al. (1993) also pointed out that the seasonal dependence of the MU radar drifts is significantly different from the solar minimum Arecibo results presented by *Ganguly et al.* [1987]. Over the MU radar, the largest and smallest daytime upward/northward drifts occur during winter and summer, respectively. The nighttime drifts are generally southward, with brief northward excursions at about 2000 and 0400 LT during equinox and summer.

The diurnal variation of the zonal drifts over the MU radar resemble the quiet time DE 2 pattern shown in Figure 8 but with much smaller average westward drifts (about 30 m/s) at about 0600 and 1300 LT. One of the main characteristics of these drifts is a well-defined semidiurnal variation. The westward radar drifts near dawn are largest during summer. The winter drifts do not show a westward velocity peak near dawn but a rather gradual increase of the westward drifts from midnight to afternoon. Notice that the Arecibo westward velocity peak is largest during winter and is absent during summer, when the drifts show essentially constant values from midnight to early afternoon. The MU drifts are eastward between about 1600 and 0300 LT, with peak values of about 60 m/s during solar maximum. These peak values occur at about 1930 LT during the equinox and summer and about an hour later during winter. The Arecibo winter data and the DE 2 observations show maximum eastward drifts occurring about 3 h later. Therefore the Arecibo, MU radar, and DE 2 results indicate the occurrence of very pronounced longitudinal variations of the zonal drifts. The longitudinal variation of the perpendicular/north drifts seems to be equally large, although this needs to be confirmed by satellite measurements.

5. DISCUSSION

Quiet Time Low-Latitude Plasma Drifts

In the absence of electric fields of magnetospheric origin, the low-latitude E and F region electrodynamic drifts are driven by E and F region dynamo electric fields. The main contributions to the daytime electric fields come from the in situ diurnal tide generated in the upper thermosphere and modified by ion drag and from (2,4) upper propagating semidiurnal tide [*Richmond et al.*, 1976]. However, additional semidiurnal tidal modes also seem to be important [*Takeda and Yamada*, 1987; *Stening*, 1989]. The semidiurnal tides become increasingly important at latitudes of 20°-30° and higher and are highly variable in time. At night the dynamo action of F region thermospheric winds generates polarization electric fields [e.g., *Rishbeth*, 1971, 1981] which strongly affect the ionospheric plasma motions. These polarization electric fields are largely short-circuited during the day by the highly conducting E region. The large scatter on the quiet time plasma drifts can be explained by the variability of low-latitude tidal winds and by the effects of E region, F region, and conjugate hemisphere dynamos. In addition, atmospheric gravity waves with periods of 1-10 h [*Earle and Kelley*, 1987] and planetary waves with periods longer than 2 days [*Chen*, 1992] can also be important sources of quiet time electric field (plasma drift) variability.

The detailed study of the dynamo action of large-scale thermospheric winds requires the use of complex numerical models [e.g., *Richmond and Roble*, 1987], which is beyond the scope of this work. We will show, however, that a qualitative understanding of the seasonal, solar cycle, and longitudinal variations of the mid- to low-latitude nighttime plasma drifts can be gained by using a simple theory of polarization electric fields driven by the F region dynamo [*Rishbeth*, 1971].

The importance of F region polarization electric fields in the nighttime Arecibo ionosphere was pointed out initially by *Behnke and Hagfors* [1974]. More detailed studies [*Burnside et al.*, 1983*b*; *Ganguly et al.*, 1987] showed that under the assumptions of equipotential magnetic field lines and of a fully developed F region polarization electric field, the northward/perpendicular and eastward components of the plasma drifts are given approximately by

$$V_{\perp N} = \sin I \frac{\int \sigma_p(h) U_x(h) ds}{\Sigma_p^n + \Sigma_p^s} \tag{1}$$

$$V_{\perp E} = \sin I \frac{\int \sigma_p(h) U_y(h) ds}{\Sigma_p^n + \Sigma_p^s} \tag{2}$$

where the integrations are performed over the entire magnetic field line, σ_p is the height-dependent Pedersen conductivity,

U_x and U_y are the northward and eastward neutral wind velocities, I is the inclination of the magnetic field (about 50° at the Arecibo and MU radars), and Σ_p^n and Σ_p^s are northern and southern hemispheric components of the field-integrated Pedersen conductivities. The time constant for the development of the nighttime polarization electric field is of the order of 200 s [*Burnside et al.*, 1983*b*].

The relationship between the F region nighttime zonal neutral winds and plasma drifts over Arecibo during magnetically quiet conditions is illustrated in Figure 9. The neutral winds were determined using Fabry-Perot Doppler shift measurements of the 630.0-nm oxygen line. Here, we have averaged the neutral wind data from 1980 through 1990 for each season, since the F region thermospheric winds are generally independent of solar flux [*Burnside and Tepley*, 1989]. The nighttime winds near the height of maximum Pedersen conductivity have smaller amplitudes than the F region winds. Thus, the nighttime F region plasma drifts are driven primarily by the F region neutral winds. In the premidnight sector, the E and F region Pedersen conductivities are comparable near solar minimum [*Harper and Walker*, 1977; *Ganguly et al.*, 1987]. This prevents the full buildup of the F region polarization electric fields during solar minimum, resulting in zonal plasma drifts significantly smaller than the corresponding neutral wind velocities for all seasons. The descent of the F region peak in the postmidnight sector causes the increase in the ratio of the F region to the E region Pedersen conductivity and consequently in the coupling between the F region neutral wind and plasma drifts during the summer and the equinoxes.

The F region Pedersen conductivity increases by a factor of about 10 from solar minimum to solar maximum, whereas the E region conductivity remains essentially unchanged [*Burnside et al.*, 1983*b*]. This leads to larger polarization electric fields and closer coupling between the neutral wind and plasma drifts during solar maxima for all seasons. The Arecibo nighttime zonal neutral winds and plasma drifts follow each other closely during summer, when the local F region conductivity largely exceeds the E region and conjugate F region values. On the other hand, the winter plasma drift and neutral wind velocities are considerably different in the premidnight sector even during periods of large solar fluxes, when the F region Pedersen conductivities are much larger than the E region values [*Burnside et al.*, 1983*b*]. This result can be explained by taking into account the effects of the conjugate E and F regions (at about 45°S, 62°W) where the summer sunset occurs about 3 h later. In this case, the Arecibo plasma drifts and neutral winds show the best agreement near midnight, when the conjugate E and F regions are in darkness. Actually, the agreement during winter solar maximum is somewhat better than indicated in Figure 10, since the winter neutral winds decrease slightly with increasing solar activity (B. Fejer, unpublished data). The early night small eastward drifts and the large westward drifts after about 0300 LT during winter result from the effects of the sunlit conjugate ionosphere [*Burnside et al.*, 1983*b*]. The equinoctial drifts are essentially an average of the solstitial results.

The nighttime zonal drifts observed over the MU radar can also be explained by the polarization fields generated by the neutral winds in the local and conjugate (at about 20°S, 136°E) ionospheres. The magnetic conjugate to the MU radar has essentially the same geographical latitude as Arecibo but in the southern hemisphere. Therefore the nighttime winter (summer) MU data should display features of the Arecibo summer (winter)

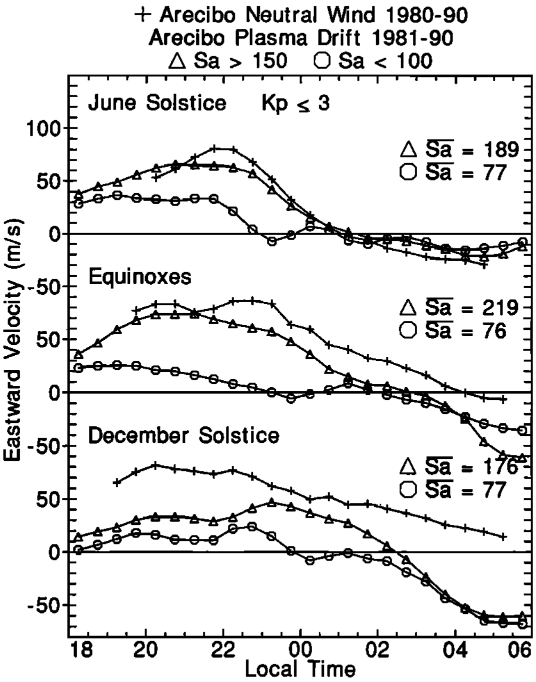

Fig. 9. Seasonal averages of nighttime F region zonal neutral winds and plasma drifts over Arecibo during magnetically quiet times. The neutral wind velocities do not change much with solar flux.

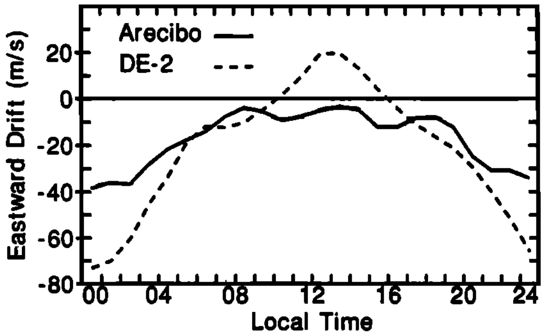

Fig. 10. Average disturbance zonal drifts obtained by subtracting the quiet time drift patterns from the Arecibo and DE 2 disturbed drifts.

drifts, which is indeed the case. The relatively small seasonal variation of the times of occurrence of maximum eastward drifts over the MU radar is also consistent with electrodynamic effects in the local and conjugate ionospheres.

The relationship between the northward/perpendicular plasma drifts and meridional neutral winds was examined by *Burnside et al.* [1983*b*] and *Ganguly et al.* [1987] for solar maximum and minimum conditions, respectively. *Behnke and Hagfors* [1974] have shown that the postmidnight northward velocity peak observed at Arecibo during equinox and winter can be explained by F region dynamo electric fields associated with the sunrise in the conjugate ionosphere. However, at other times, local and conjugate E and F region neutral wind and conductivity effects are not as evident on the Arecibo northward/perpendicular plasma drifts as on the zonal drifts.

The parallel ion drifts are generally anticorrelated to the northward/perpendicular plasma drifts [e.g., *Behnke*, 1971; *Behnke and Hagfors*, 1974; Oliver et al., 1993], although this relationship is not always evident on our average data, particularly near solar maximum. This anticorrelation can be caused by ion drag, F region dynamo, and electric field and ion diffusion [*Walker*, 1980]. Oliver et al. (1993) attributed the anticorrelation of the MU radar drifts to ion drag and F region dynamo effects during the day and night, respectively. The local and conjugate hemisphere E and F region electrodynamic effects discussed above should affect and be affected by the longitudinal variation of the neutral winds.

Disturbance Plasma Drifts

Figure 6 indicates that the daytime northward/perpendicular plasma drifts decrease during magnetically active conditions, whereas the nighttime drifts remain essentially unchanged. This decrease corresponds to an average daytime westward disturbance (relative to the quiet time value) electric field of about 0.6 mV/m. Figure 10 presents the seasonally averaged Arecibo and DE 2 disturbance drifts obtained by subtracting the average quiet time values from the disturbed ones. These plasma drifts are westward at essentially all local times, corresponding to northward electric fields. The daily variations of the radar and satellite zonal perturbation drifts are in good agreement even though the amplitudes are significantly different. F region average zonal drifts over Millstone Hill [*Buonsanto et al.*, 1993] also show closer agreement with the corresponding DE 2 data during disturbed conditions than during quiet periods. This confirms the larger longitudinal variation of the quiet time drifts.

The magnetospheric and ionospheric dynamos are additional sources of ionospheric electric fields during periods of high magnetic activity. Model calculations [e.g., *Senior and Blanc*, 1984; *Fejer et al.*, 1990] suggest that the low-latitude electric fields associated with an increase in high-latitude convection are eastward during the day and westward at night, whereas the meridional electric field perturbations are northward except for the 0200-0900 magnetic local time. For sudden decrease in the high latitude convection, the polarities of the electric field perturbations are reversed. These electric field perturbations are short-lived (time scales of 1-2 h) and therefore tend to cancel out on the average low-latitude electric field (drift) data. The ionospheric disturbance dynamo electric fields and plasma drifts, produced by high-latitude frictional and Joule heating, have longer lifetimes and latitude-dependent time delays [*Blanc and Richmond*, 1980]. The low-latitude meridional disturbance dynamo drifts are southward/perpendicular (corresponding to a westward electric field) during the day and eastward at night, while the zonal drifts are westward at all local times. The polarities of the disturbance drifts shown in Figures 6 and 10 are in good agreement with the disturbance dynamo results except for those of the nighttime meridional drifts.

In a recent study, *Mendillo et al.* [1992] have shown that the geometry of the magnetic field, resulting from the displacement between the geographic and geomagnetic equators and also from magnetic declination effects, controls the effects of storm time electric fields and thermospheric winds on the ionospheric F 2 layer. We have seen that the disturbance electric fields and plasma drifts show a more consistent pattern in magnetic than in geographical coordinates. Our results also show that the quiet time Arecibo plasma drifts are strongly affected by the geometry of the magnetic field because of the electrodynamic processes along the entire magnetic field line. This suggests that the drift velocities measured in the American sector, equatorward of the auroral zone, are not representative of the plasma drifts from other longitudinal sectors. In addition, since the plasma drifts during quiet time and disturbance drifts have different longitudinal dependence, the net effect is a complex longitudinal variation which depends also on magnetic activity.

6. CONCLUSIONS

We have examined the seasonal and solar cycle dependences of the Arecibo F region plasma drifts. These results can be qualitatively explained as resulting from electrodynamic effects in the local and conjugate ionosphere. The plasma drifts over Arecibo are not representative of similar data from other longitudinal sectors as a result of the unique displacement between the geomagnetic and geographic equators and magnetic declinations in the American sector. The disturbance drift patterns observed over Arecibo are consistent with disturbance dynamo effects and are typical of those from other sites at the same dip latitude. Extensive global plasma drift and electric field data will be required for the development of realistic global ionospheric electric field models.

Acknowledgments. I thank R. Burnside and C. Tepley for the Arecibo radar and optical measurements. I also thank R. Heelis, A. Richmond, and K. Miller for helpful discussions and D. Haroldsen and D.-B. Zhang for help with the data. This work made use of the CEDAR data base at NCAR, which is supported by the National Science Foundation. The Arecibo Observatory is operated by Cornell University under a cooperative agreement with the National Science Foundation. This work was supported by the Aeronomy Program of the National Science Foundation through grants ATM-9120263 and ATM-9202790 and by the National Aeronautics and Space Administration through grant NAGW-2103.

The Editor thanks T. J. Fuller-Rowell and another referee for their assistance in evaluating this paper.

REFERENCES

Behnke, R. A., Vector measurements of the ion transport velocity with applications to F-region dynamics, Ph.D. thesis, Rice University, Houston, Tex., 1971.

Behnke, R. A., and T. Hagfors, Evidence for the existence of nighttime F region polarization fields at Arecibo, *Radio Sci.*, *9*, 211-216, 1974.

Behnke, R. A., and R. M. Harper, Vector measurements of *F* region ion transport at Arecibo, *J. Geophys. Res.*, *78*, 8222-8234, 1973.

Berkey, J. E., A. D. Richmond, R. M. Barnes, S. Gonzalez, and C. A. Tepley, Solar cycle variations in F-region electrodynamic drifts at Arecibo, *J. Geophys. Res.*, *95*, 4303-4306, 1990.

Blanc, M., and A. D. Richmond, The ionospheric disturbance dynamo, *J. Geophys. Res.*, *85*, 1669-1686, 1980.

Buonsanto, M. J., M. E. Hagan, J. E. Salah, and B. G. Fejer, Solar cycle and seasonal variations in the F region electrodynamics at Millstone Hill, *J. Geophys. Res.*, in press, 1993.

Burnside, R. G., and C. A. Tepley, Optical observations of the thermospheric neutral winds at Arecibo between 1980 and 1987, *J. Geophys. Res.*, *94*, 2711-2716, 1989.

Burnside, R. G., R. A. Behnke, and J. C. G. Walker, Meridional neutral winds in the thermosphere at Arecibo: Simultaneous incoherent scatter and airglow observations, *J. Geophys. Res.*, *88*, 3181-3189, 1983*a*.

Burnside, R. G., J. C. G. Walker, R. A. Behnke, and C. A. Gonzalez, Polarization electric fields in the nighttime F layer at Arecibo, *J. Geophys. Res.*, *88*, 6259-6266, 1983*b*.

Burnside, R. G., C. A. Tepley, M. P. Sulzer, T. J. Fuller-Rowell, D. G. Torr, and R. G. Roble, The neutral thermosphere at Arecibo during geomagnetic storms, *J. Geophys. Res.*, *96*, 1289-1301, 1991*a*.

Burnside, R. G., C. A. Tepley, and M. P. Sulzer, World Day observations at Arecibo: 1985 to 1989, *J. Geophys. Res.*, *96*, 3691-3710, 1991*b*.

Chen, P.-R., Two-day oscillation of the equatorial ionization anomaly, *J. Geophys. Res.*, *97*, 6343-6357, 1992.

Earle, G. D., and M. C. Kelley, Spectral studies of the sources of ionospheric electric fields, *J. Geophys. Res.*, *92*, 213-224, 1987.

Fejer, B. G., Low latitude electro-dynamic plasma drifts: A review, *J. Atmos. Terr. Phys.*, *53*, 677-693, 1991.

Fejer, B. G., et al., Low and mid-latitude ionospheric electric fields during the January 1984 GISMOS campaign, *J. Geophys. Res.*, *95*, 2367-2377, 1990.

Fejer, B. G., E. R. de Paula, S. A. González, and R. F. Woodman, Average vertical and zonal F-region plasma drifts over Jicamarca, *J. Geophys. Res.*, *96*, 13901-13906, 1991.

Fukao, S., W. L. Oliver, Y. Onishi, T. Takami, T. Sato, T. Tsuda, M. Yamamoto, and S. Kato, F region seasonal behavior as measured by the MU radar, *J. Atmos. Terr. Phys.*, *53*, 599-618, 1991.

Ganguly, S., R. A. Behnke, and B. A. Emery, Average electric field behavior in the ionosphere over Arecibo, *J. Geophys. Res.*, *92*, 1199-1210, 1987.

Gonzales, C. A., M. C. Kelley, R. A. Behnke, J. F. Vickrey, R. Wand, and J. Holt, On the latitudinal variations of the ionospheric electric field during magnetospheric disturbances, *J. Geophys. Res.*, *88*, 9135-9144, 1983.

Harper, R. M., and J. C. G. Walker, Comparison of electrical conductivities in the E and F regions of the nocturnal ionosphere, *Planet. Space Sci.*, *25*, 197-199, 1977.

Heelis, R. A., and W. R. Coley, East-west ion drifts at mid-latitudes observed by Dynamics Explorer-2, *J. Geophys., Res.*, *97*, 19,461-19,469, 1992.

Kelley, M. C., *The Earth's Ionosphere*, pp. 187-259, Academic, New York, 1989.

Mendillo, M., S.-Q. He, and H. Rishbeth, How the effects of winds and electric fields in the F-2 layer vary with latitude and longitude: A theoretical study, *Planet. Space Sci.*, *5*, 595-606, 1992.

Oliver, W. L., S. Fukao, T. Sato, T. Tsuda, S. Kato, I. Kimura, A. Ito, T. Saryou, and T. Araki, Ionospheric incoherent scatter measurements with the MU radar: Observations of F-region electrodynamics, *J. Geomagn. Geoelectr.*, *40*, 963-985, 1988.

Richmond, A. D., and R. G. Roble, Electrodynamic effects of thermospheric winds from the NCAR thermospheric general circulation model, *J. Geophys. Res.*, *92*, 12,365-12,376, 1987.

Richmond, A. D., S. Matsushita, and J. D. Tarpley, On the mechanism of electric currents and fields in the ionosphere, *J. Geophys. Res.*, *81*, 547-555, 1976.

Richmond, A. D., et al., An empirical model of quiet-ionospheric electric fields at middle and low latitudes, *J. Geophys. Res.*, *85*, 4658-4664, 1980.

Rishbeth, H., Polarization fields produced by winds in the equatorial F-region, *Planet. Space Sci.*, *19*, 357-369, 1971.

Rishbeth, H., The F-region dynamo, *J. Atmos. Terr. Phys.*, *41*, 387-392, 1981.

Rishbeth, H., S. Ganguly, and J. C. G. Walker, Field-aligned and field perpendicular velocities in the ionospheric F-2 layer, *J. Atmos. Terr. Phys.*, *40*, 767, 1978.

Senior, C., and M. Blanc, On the control of magnetospheric convection by the spatial distribution of ionospheric conductivities, *J. Geophys. Res.*, *89*, 261-284, 1984.

Stening, R. J., A calculation of ionospheric currents due to semidiurnal antisymmetric tides, *J. Atmos. Terr. Phys.*, *94*, 1525-1531, 1989.

Sulzer, M. P., A phase modulation technique for a sevenfold statistical improvement in incoherent scatter data-taking, *Radio Sci.*, *21*, 737-744, 1986.

Takeda, M., and Y. Yamada, Simulation of ionospheric electric fields and geomagnetic field variation by the ionospheric dynamo for different solar activity, *Ann. Geophys.*, *5*, 429-434, 1987.

Walker, J. C. G., Correlation of wind and electric field in the nocturnal F region, *Geophys. J. R. Astron. Soc.*, *60*, 85-94, 1980.

Wand, R. H., A model representation of the ionospheric electric field over Millstone Hill ($\Lambda = 56°$), *J. Geophys. Res.*, *86*, 5801-5808, 1981.

B. G. Fejer, Center for Atmospheric and Space Sciences, Utah State University, Logan, UT 84322-4405.

(Received October 19, 1992
revised February 25, 1993
accepted March 31, 1993.)