DE-2 observations of morningside and eveningside plasma density depletions in the equatorial ionosphere

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Abstract. The occurrence of equatorial density depletions in the nightside F region ionosphere has been investigated by using observations gathered by the polar-orbiting Dynamics Explorer 2 satellite from August 1981 to February 1983. A variety of electric field/plasma drift patterns were observed within these depletions, including updrafting, downdrafting, bifurcating, converging, subsonic, and supersonic flows. The depletions, 116 events in total, are distributed over two groups: group I (eveningside depletions) consists of the events in the 1900-2300 MLT sector, and group II (morningside depletions) are the events in the 2300-0600 MLT sector. A statistical analysis reveals clear differences in the density depletion occurrence rates between the two groups. Magnetic activity appears to suppress the generation of eveningside depletions with a delay of 2-3 hours. In the morningside the probability of observing depletions increases instantly with increasing magnetic activity; yet the best correlation is found with a 2-hour delay. This indicates that in the premidnight sector the substorm-induced dynamo and prompt penetration electric fields induce westward electric fields in the equatorial ionosphere 2 hours after the onset in the auroral region. In the postmidnight sector, high-latitude ionospheric disturbances induce instantly equatorial eastward electric fields that move the F layer to higher altitudes, where it can become unstable to the Rayleigh-Taylor instability. Eveningside depletions were observed at all longitudes except those over the Pacific Ocean, while the morningside depletions occurred mostly over the Pacific and Atlantic-African sectors.

1. Introduction

Upward moving depleted plasma flux tubes in the equatorial F region ionosphere, a phenomenon also called equatorial spread F or equatorial bubbles, result from the Rayleigh-Taylor (RT) instability acting on the nighttime bottomside F region plasma density gradient. The occurrence of these depletions depends essentially on the altitude of the F layer, which, in turn, is controlled by dynamo actions in the equatorial ionosphere. The normal F region dynamo generates eastward electric fields during daytime and westward electric fields during nighttime [e.g., Kelley, 1989], corresponding to upward and downward motion of the layer, respectively.

After sunset at about 1800 MLT, the equatorial F layer frequently rises quickly to higher altitudes owing to enhanced eastward electric fields that occur at this local time at the equator [e.g., Farley et al., 1986]. At about 1900 MLT, the rising speed decelerates, and after about 2000 MLT the F layer begins descending. When the F layer has risen to an altitude where the ion-neutral collision frequency is small, the local RT instability becomes susceptible to triggering by some initial seed mechanism, possibly by gravity waves [e.g., Huang and Kelley, 1996a; Singh et al., 1997a].

Equatorial F region plasma density depletions are most frequently observed in the premidnight sector between 2000 and 2300 MLT, as shown in the large quantities of in situ and ground-based data [e.g., Farley et al., 1970; Woodman and LaHoz, 1976; McClure et al., 1977; Hysell et al., 1994]. There are also observations of depletions in the postmidnight sector [e.g., Bowman,
where the occurrence of depletions is (1) always high, during equinox periods. Recently, the growth rate of RT instability (for details, see Mendillo during northern summer, and at South American and longitudes during northern winter, at Pacific longitudes ous at the conjugate E layers, leading to a maximum omagnetic flux tubes. Then the sunset is simultane- sunset terminator is approximately aligned with the ge- on the seasonal-longitudinal dependence of depletions 

jet [1991], and Fejer and Scherliess [1995]. Basically, the high-latitude ionospheric current systems can affect the low-latitude electrodynamics in two different ways: The first possibility is the prompt penetration of auroral electric fields into the equatorial latitudes following large and sudden changes in the cross polar cap poten- tial. These electric fields are short-lived (1-2 hours) and propagate almost instantly to low latitudes [Fejer, 1991]. In the equatorial region, the prompt penetration electric fields are westward (i.e., they drive downward plasma motions) following sudden increases in high-latitude convection and eastward following sudden decreases. The second possibility is the disturbance dynamo effect, suggested by Blanc and Richmond [1980]. During magnetic disturbances the auroral ionosphere is heated through Joule dissipation of auroral currents and through energetic particle precipitation, which create large thermospheric winds propagating to low latitudes with some time delay. In the equatorial region the neutral winds drive long-lived (several hours) electric fields, which are westward in the premidnight sector and eastward in the postmidnight sector. These fields also maximize during equinox solar maximum conditions and probably depend on longitude [Fejer et al., 1999]. According to Blanc and Richmond [1980], the delay time to the strongest disturbances in the equatorial region is 9 hours, but recent radar studies [e.g., Fejer and Scherliess, 1995] suggest delays of only a few hours. The disturbance dynamo tends to diminish the effect of the normal dynamo in the premidnight sector. It has been suggested that global magnetic activity could suppress the generation of the eveningside depletions [Burke, 1979; Singh et al., 1997b]. The connection between morningside depletions and magnetic activity has been known to exist, and their relation has been investigated to some extent [e.g., Bowman, 1978; Singh et al., 1997b].

Other parameters can also affect the generation of the depletions. For instance, Tsunoda [1985] reported on the seasonal-longitudinal dependence of depletions and found that the "spread F season" occurs when the sunset terminator is approximately aligned with the geomagnetic flux tubes. Then the sunset is simultane- ous at the conjugate E layers, leading to a maximum growth rate of RT instability (for details, see Mendillo et al. [1992]). The spread F season occurs at Atlantic longitudes during northern winter, at Pacific longitudes during northern summer, and at South American and Indian longitudes during equinox periods. Recently, McClure et al. [1998] showed that there are longitudes where the occurrence of depletions is (1) always high, (2) high in one solstice and near zero in the other, (3) high in one solstice and moderate in the other three seasons, (4) high in all but one season, and (5) always moderate.

In this paper we investigate the occurrence rates of eveningside (1900-2300 MLT) and morningside (2300-0600 MLT) equatorial density depletions by utilizing measurements of the Dynamics Explorer 2 (DE 2) satellite in years 1981-1983. Section 3 presents examples of DE 2 observations of eveningside and morningside equatorial density depletions and their associated electric fields, plasma drifts, and irregularities. In section 4 we present the statistical results of the 116 depletions encountered by DE 2. The occurrence rates of depletions in the evening and morning sectors are investigated separately, and the observed differences between these two groups are discussed in section 5. We concen- trate on the effects of the global magnetic activity and geographical longitude on the occurrence of equatorial density depletions.

2. Instrumentation

The DE 2 satellite was a low-altitude (periapsis 309 km, apoapsis 1012 km) polar-orbiting NASA satellite launched on August 3, 1981 [Hoffman et al., 1981]. We present data from the in situ electric field instrument (VEFI) [Maynard et al., 1981], the Langmuir probe (LANG) [Krehbiel et al., 1981], and the ion drift meter (IDM) [Heelis et al., 1981]. We also studied magnetic field fluctuations during depletion encounters by using data from the magnetometer [Farthing et al., 1981] on board the satellite. However, except for one supersonic depletion event, studied in detail by Aggson et al. [1992b], no magnetic fluctuations were observed, and thus magnetic fields are not included in this paper. In this paper we adopt a fixed coordinate system, where x points southward, y points radially upward, and z points westward. This is regardless of whether the satellite was traversing the equator from the north or from the south and regardless of its rotations every 6 months to avoid thermal extremes.

The VEFI measured DC electric fields in the range of ±1 V/m with a resolution of 0.1 mV/m at a sampling rate of 16 measurements per second, using a symmetric double floating probe technique with six 11-m rigid cylindrical antennas deployed along three orthogonal axes. Unfortunately, the antenna pair along the spacecraft z axis did not deploy, and therefore vertical plasma drift speeds (due to $E \times B$ motions) cannot be obtained from VEFI measurement. The AC electric field power levels from 4 Hz to 512 kHz were monitored with a 20-channel comb filter spectrometer in the amplitude resolution of 1 $\mu$V/m to 10 mV/m. Filters 1-8 and 9-16 cover the 4- to 1024-Hz range in the last of two logarithmically spaced filters from two perpendicular double probes. Filters 17-20 cover the 1024-Hz to 512-kHz range; these filters are not used in this study. We use a temporal resolution of 1/0.5 s in this study.
The DE 2 measured complete three-dimensional ion drift velocity by using two separate instruments: the retarding potential analyzer (RPA) [Hanson et al., 1981] measured the velocity component parallel to the velocity vector of the spacecraft ($v_x$), and the IDM measured ion drift components perpendicular to the velocity vector of the spacecraft ($v_y$ and $v_z$). The velocity range of IDM was ±4000 m/s with an accuracy of ±50 m/s. Although the high resolution was 1/32 s, we use the resolution of 1/2 s. The ion density is obtained from the RPA, and the electron density, which we use, is from the Langmuir probe. The density measurements gathered by both instruments were compared and found clearly similar.

3. Observations

We define an equatorial density depletion as an event where the VEFI AC electric field shows clear wave activity simultaneously with a plasma density “bite-out” visible in the LANG data. In most of the events the density decreased an order of magnitude; in all events the density decreased at least 40%. Figure 1a shows a DE 2 traversal across a depletion channel viewing from the east, whereas Figure 1b shows the same viewing from above in the case of nontilted and tilted depletion. Because of its polar orbit, DE 2 tended to move along the depleted flux tube (see Figure 1a), and therefore the time the satellite usually stayed within the depletions was of the order of minutes or less.

The altitude range of the satellite was higher in the beginning of the mission, and the detection altitude of depletions varied seasonally owing to the satellite orbit configuration. The depletions were detected throughout the altitude range of 250-850 km. During 95% of the satellite lifetime the solar flux index was 100-250, indicating that the depletions were observed during high solar flux conditions.

The DE 2 satellite encountered equatorial density depletions which were characterized by a variety of plasma flows, such as updrafting, downdrafting, subsonic, supersonic, bifurcating, and converging flows. Depletions with no perpendicular plasma flows, called dead bubbles by Aggson et al. [1992a], were also detected. In the following sections, we present representative examples of equatorial plasma depletions in the eveningside and morningside.

3.1. Eveningside Plasma Depletion Events

Figure 2 presents an example of an eveningside updrafting plasma depletion which occurred on October 26, 1981, at ~1622 UT, about 640 km above the Indian Ocean (~62° geographic longitude) at 2000 MLT. The top panel shows a frequency-time spectrogram of the AC electric field fluctuations (millivolts per meter) for filters 1-8 measured by the VEFI instrument; the gray scale is given above the panel. The next five panels are the electron density in logarithmic scale (electrons per cubic centimeter), the $E_y$ component (millivolts per meter), the $E_xB$ ion drift vectors in the yz plane (positive axis upward and westward) based on the ion drift components, and the $y$ and $z$ components of the ion drift velocity (meters per second).

The electron density shows an extended plasma depletion region with upward plasma flows centered at approximately 1622:22 UT and 1623:05 UT. The background $E_y$ is negative, corresponding to an eastward ambient $E_xB$ drift, which is in accordance with background ion drift $v_y$ data. During the event the ambient plasma is drifting downward, but at 1622:22 UT $v_y$ suddenly becomes positive, indicating that the plasma drifts upward with a velocity of about 100 m/s. At the same time, $E_y$ becomes less negative, suggesting
that although the plasma still drifts eastward, the flow is more vertically oriented. The same feature is also shown by $v_z$. One may conclude that the plasma is moving upward in the depleted eastward tilted channel. The second region of upward flow at about 1623:05 UT is tilted more eastward. These two upward flows may belong to the same channel. First, the upper and narrower part of the channel is crossed, then the satellite moves at the edge of the channel, and finally, as the satellite altitude and latitude decrease, a lower, wider, and more eastwardly tilted part of the same channel is detected. This is a typical eveningside event in the DE 2 database. The depletion is extended, because the satellite is moving along the depletion channel as it is aligned along the direction of the spacecraft's velocity (cf. Figure 1).

**3.2. Morningside Plasma Depletion Events**

Figure 3 presents an example of a morningside depletion event on 30 June, 1982, at ~0849 UT, 614 km above the west coast of South America at 0400 MLT. The format is the same as in Figure 2. The AC electric fields show turbulence in the frequency range of 4 - 256 Hz. Electron density decreases by about half a magnitude, while $E_y$ shows a positive signature indicating westward $E \times B$ drift. This can also be seen in $v_z$, where the drift velocity peak is about 150 m/s and positive. The upward velocity is over 200 m/s. The magnetic conditions were quite disturbed; the $K_p$ index was 5, whereas the maximum $AE$ index of the day was 1100 nT at 0320 UT, 5.5 hours before the depletion encounter. At 0530 UT, on an earlier equatorial encounter, the average $F$
region vertical velocity was 12 m/s upward, and now a few minutes before the depletion observation the average upward velocity was 56 m/s. Thus the $F$ layer was indeed rising over several hours as a consequence of magnetic activity; according to the quiet time pattern, vertical speeds should be downward at this local time sector.

3.3. Other Observed Depletion Events

Although downward plasma drifts within a depletion channel are not commonly observed, Laakso et al. [1994] reported on such an event found in the San Marco D satellite database. The appearance of a downdrafting plasma depletion requires favorable conditions, such as westward electric fields, which give a downward $E \times B$ drift velocity at low altitudes. Westward fields are common in the equatorial ionosphere after about 2000 MLT, when the $F$ region usually starts descending. One downdrafting event was found from the DE 2 database, and it was detected in the morningside (0400 MLT) 370 km above the Pacific Ocean during a magnetically disturbed period ($K_p = 5$).

Sometimes equatorial $F$ region plasma depletion channels bifurcate into separate channels [Aggson et al., 1996; Laakso et al., 1997]. Bifurcation has often been related to the Pedersen conductivities inside and outside the depletion [McDonald et al., 1981] and the zonal size of the depletion channel [Huang and Kelley, 1996b]. Bifurcation is believed to be a fairly common feature, although it cannot be observed very often in the DE 2 database because of the polar orbit of the satellite. In fact, the only favorable place for detecting bifurcating

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**Figure 3.** Morningside updrafting plasma depletion with a westward tilting. Plasma drifts at a velocity of over 200 m/s in the depleted region.
flows by DE 2 is the South Atlantic anomaly region, where the magnetic equator is not aligned in the east-west direction. Indeed, a bifurcating plasma depletion event from the DE 2 database was detected 740 km above the South Atlantic anomaly region in the evening-side (2100 MLT) during a magnetically disturbed period (Kp - 4 throughout the day).

Aggson et al. [1992a] suggested that the equatorial density depletions can generally be divided into two groups, "live" and "dead" ones. Live depletions are connected to the driving RT instability force in the bottomside F region, while the dead depletions have lost their connection to it. Aggson et al. [1992a] also found that in most live depletions the walls are collapsing inward, which may lead to the pinching-off process and therefore to the death of the depletions. In the case of dead plasma depletions, the measurements show density "bite-outs" and the presence of wave activity particularly at low frequencies, but no noticeable change in the vertical plasma drift is observed at the same time. Several dead depletion events were found from the DE 2 database.

4. Statistical Results

Since the plasma depletions are directed along the magnetic field lines, the polar-orbiting DE 2 usually observed only one depletion at each equator cut, except for the South Atlantic anomaly region, where the orbit trajectory and the magnetic field have a large angle. However, for statistical purposes, the occurrence of multiple depletions is counted as a single event. From the period of August 1981 to February 1983, the total amount of equatorial encounters with depletion events was 116. Because of its polar orbit, DE 2 can traverse the equator between depletions, and thus all the events may not have been detected. This is, however, somewhat unlikely, because the depletions are usually tilted (see e.g. Woodman and LaHoz [1976] and figures therein). The parameters, whose influence on the depletions are investigated, are local time, Kp index, and geographical longitude.

The orbit plane of DE 2 rotated about the Earth so that all local time sectors are covered in 6 months. This means that a certain local time sector is sampled only during a certain month. Figure 4a presents an MLT versus month histogram which shows the number of those equatorial crossings where data were returned to the ground. The satellite lifetime from August 1981 to February 1983 covers two fall and winter periods and only one summer and spring period. Therefore the gray shades at fall and winter periods are deeper. Figure 4b shows a longitude versus month histogram, indicating that all longitudes were sampled relatively equally and that the Peruvian sector had the largest number of samples.

Figure 5 presents the local time distribution of depletion events. Figure 5a shows the total number of the equator crossings in which the DE 2 satellite gathered data. Figure 5b presents the number of equatorial cuts with depletion events, whereas Figure 5c is the ratio of Figures 5a and 5b, thus representing the occurrence rate of depletions at each local time sector. In Figure 5a we see that the afternoon, evening, and morning local time sectors are oversampled owing to the fact that the satellite measured those local time sectors during spring and fall, and there are two fall periods in the lifetime of DE 2 (see Figure 4). The interlocking of the season and local time of the DE 2 measurements might have some effect on the local time variation. We can see from the figure that the probability of observing a
depletion rapidly increases after 1900 MLT, reaching a peak (~40%) at 2100 MLT. As was mentioned, the \( F \) layer usually starts falling down at 2000 MLT, indicating that the peak in the depletion occurrence rate is seen during a descending \( F \) layer, which is consistent with previous studies [e.g., Kelley et al., 1981]. At 2200 MLT the occurrence rate decreases, which may not be statistically significant, since there is only a small number of samples in this local time sector. At 2300 MLT the probability is again on a level, where the occurrence rate is only slightly less than the rate at 2100 MLT, although the \( F \) region is expected to lie at a low altitude. This implies that the peak at 2300 MLT cannot be related to the normal behavior of the \( F \) region. Therefore we study the occurrence rates of depletions for two groups, in the eveningside at 1900 - 2300 MLT and in the morningside at 2300 - 0600 MLT.

4.1. Plasma Depletions in the Evening Sector (1900-2300 MLT)

The \( Kp \) index delayed by 2 hours is used to characterize plasma depletion dependence on global magnetic activity, where a 2-hour delayed \( Kp \) means the \( Kp \) value 2 hours before the hour of depletion observation. Figure 6 presents the results for the evening sector 1900-2300 MLT. Figure 6a displays the distribution of 2-hour delayed \( Kp \) values during all equator cuts at 1900-2300 MLT. The last bin represents the bin range from \( Kp = 4 \) to \( Kp = 9 \), i.e., bins summed together to improve the statistical sampling; no depletions were observed when \( Kp > 8 \). Figure 6b shows the number of equatorial cuts with depletions, and Figure 6c is the normalized depletion occurrence rate, obtained by dividing Figure 6a by Figure 6b. The distribution decreases with increasing
magnetic activity in Figure 6c and thus on the basis of the statistics, we conclude that the magnetic activity decreases the number of depletions in the evening sector with a delay time of 2 hours.

We have also studied the depletion dependence on Kp with other time delays. Figure 7 shows the normalized depletion occurrence rates as functions of 0- to 9-hours delayed Kp index. The panels have been obtained the same way as Figure 6c. For 0-1 hours, the probability of observing eveningside depletions is independent of global magnetic activity. For a 2-hour delay, the number of depletions is best suppressed by magnetic activity. A weaker inverse correlation is seen with time delays of more than 2 hours, and surprisingly a good inverse correlation will appear again with a 9-hour delay.

Figure 8 displays results for the longitude dependence of the eveningside depletions; the longitude is binned by 30°. The format of the figure is similar to that of Figure 6. According to Figure 8a, all the longitudes were sampled quite equally, providing good statistics. The depletion probability is largest over the Atlantic-African sector, whereas above the Pacific Ocean the depletion probability is smallest.
probability is clearly small. DE 2 observed depletions in the 1900-2300 local time sector from September to November and in April. A longitudinal variation with season is expected, as our evening events are collected approximately in the northern spring and late fall. This longitude dependence visible in Figure 8 is partly due to the seasonal-longitudinal effect as described by Tsunoda [1985].

4.2. Plasma Depletions in the Morning Sector (2300-0600 MLT)

The dependence of the plasma depletion occurrence rate on delayed $K_p$ index and longitude was also studied for the morningside events. Figure 9 shows the results for 2-hour delayed $K_p$ index. The format of the figure is the same as that of Figure 6 except that the last bin includes $K_p = 5-9$. According to Figure 9c the depletions in the morning sector appear to develop in such a manner that they are correlated with global magnetic disturbances, which is compatible with the predictions made in previous studies [Bowman, 1978; Burke, 1979; Singh et al., 1997b]. Based on these statistics, the probability of occurrence is less than 5% during magnetically quiet periods, while during magnetically disturbed periods this probability is almost 15%.

Figure 10 presents the normalized depletion occurrence rates versus 0- to 9-hours delayed $K_p$ indices. The correlation between depletion occurrence and magnetic activity is instantly seen, as the probability of observing depletions in the morningside increases with increasing nondelayed $K_p$; yet the best correlation is seen with a 2-hour delayed $K_p$. Weaker correlation is observed with
delay times of 3-4 hours, whereas for time delays of 5-6 hours the global magnetic activity does not affect the probability of observing morningside depletions. Some correlation is again seen for time delays of more than 7 hours.

Figure 11 presents the dependence of the occurrence rate on longitude for the 2300-0600 MLT events. The format of the figure is the same as that of Figure 8. Figure 11a shows that all longitudes were equally sampled. The normalized occurrence rate of morningside depletions over longitude is rather different from that of the eveningside depletions (see Figure 8c). The maximum probability is seen over the Pacific Ocean and again in the Atlantic-African region, while in the Indian sector the probabilities are clearly smaller. These depletions were detected approximately during northern winter and summer.

Figure 9. (a) Number of 2-hour delayed Kp indices during equatorial crossings in the local time sector 2300-0600. (b) Number of equatorial crossings with density depletions plotted against the 2-hour delayed Kp index. The Kp indices 5-9 are summed together to the last bin. (c) Normalized morning depletion occurrence rate as a function of 2-hour delayed Kp index.

Figure 10. Morningside normalized depletion occurrence rates versus 0-9 hours delayed Kp index
5. Discussion

5.1. Dependence of Plasma Depletions on $K_p$

It has been suggested that with increasing magnetic activity the probability of observing equatorial $F$ region plasma depletions decreases in the premidnight sector (see, e.g., Burke [1979] and Singh et al. [1997b]). This could be due to a westward electric field buildup in the premidnight sector a few hours after the magnetic disturbances [Blanc and Richmond, 1980]. The disturbance dynamo effects must be superimposed upon the normal dynamo effects, which remain active during magnetic disturbances. This does not suggest that the generation of plasma depletions is totally inhibited, but the probability of observing them is reduced in the disturbed ionosphere.

The observations presented here support this conclusion. Blanc and Richmond [1980] suggest that the delay time between the onset of a substorm and strongest electric fields in equatorial region is 9 hours, whereas Fejer and Scherliess [1995] suggest a time delay of only a few hours. Our results suggest that the best inverse correlation between magnetic activity and depletion occurrence rate appears at a 2- to 3-hour delay. For time delays of less than 2 hours, the depletion occurrence rate is independent of global magnetic activity, whereas time delays of more than 2 hours show weak inverse correlation. With a 9-hour time delay the inverse correlation is again enhanced. Therefore our results surprisingly support the suggestion of both Blanc and Richmond [1980] and Fejer and Scherliess [1995]. Notice also that the correlation between the depletions and magnetic activ-
ity depends on the solar cycle and the season; for example, Fejer et al. [1999] found some anticorrelation between eveningside density depletions and magnetic activity in the American sector during equinox periods. This is consistent with our results for 0- to 1-hour delayed $Kp$ indices, since DE 2 data are largely from equinox, although the satellite data are obviously not restricted to the American sector.

The situation is different in the postmidnight sector, where the disturbance dynamo and the prompt penetration electric fields create eastward electric fields in the equatorial $F$ region [Blanc and Richmond, 1980; Fejer, 1991]. Such fields raise the $F$ layer, which can lead to the development of depletions, since the growth rate of RT instability becomes large in high altitudes owing to smaller ion-neutral collision frequency. Figure 9c clearly shows that with increasing 2-hour delayed $Kp$ index the occurrence rate of morningside depletions increases, which is also observed with nondelayed $Kp$. Fejer et al. [1999] show that the spread $F$ activity decreases from solar minimum to solar maximum. Since almost all of the morningside depletions were detected during high solar flux conditions, this could also be of some importance in this study.

However, notice that these statistics deal with the conditions prior to the observation of the depletions and not with the conditions necessary for their generation. That is, when DE 2 observed a depletion, we have no information about the exact geomagnetic conditions that might have generated them. This is particularly the case for dead and perhaps also for downdrafting depletions which could have been generated a few hours before they were observed by the DE 2 satellite. This introduces an uncertainty on the exact time delays particularly in the postmidnight sector.

5.2. Dependence of Plasma Depletions on Longitude

The observations on the longitude dependence are more difficult to interpret. In the eveningside (1900-2300 MLT), depletions tend to occur anywhere else but above the Pacific Ocean. We observe a high depletion probability over the Atlantic-African and South American sectors, an almost 30% depletion probability in the Indian sector, and a lack of depletions over the Pacific Ocean; this is in accordance with recent observations of McCue et al. [1998]. Kil and Heelis [1998] found that the probability of observing depletions is always high in the Atlantic-African sector, regardless of the season, because the seed perturbations of the RT instability (e.g., gravity waves) may be maximized there owing to weather conditions. Some of the depletions can be explained in terms of the spread $F$ season described by Tsunoda [1985]. Namely, he found that the eveningside depletions vary with longitude, depending on whether the sunset is simultaneous at conjugate points of the $E$ layer, which depends on the season. Our observations were made during spring and late fall, which are favorable seasons for depletion development in the Indian and South American sectors [Tsunoda, 1985].

There is a region over the Pacific Ocean (peak at longitudes of -120° to -90° in Figure 8c) where depletion probability is 30%. A possible explanation for the peak is that the region may have been favorable for the generation of initial seeds of RT instability. Otherwise, the cause of this enhanced depletion activity remains unexplained; however, we have observed that during and before these depletion events there was some hurricane activity on the observation longitudes. Almost all of the Pacific depletions were detected in October 1981 and 1982, i.e., during the hurricane season in the Pacific. Notice also the dip in depletion occurrence rate above the Peruvian sector. Figure 4b shows that the Peruvian sector (-60° to -90°) has the highest sample rates except for April, May, and July, when the sampling rate was at the same level as that in the other longitude sectors. Figure 4a shows that for April, May, and July DE 2 measured local time sectors 2000-2200, 1700-2100, and 0100-0500, respectively. The other months when the eveningside depletions are monitored in the Peruvian sector are September and October, when the Peruvian sector clearly has the largest number of counts. Therefore we believe that there is at least a sufficient number of counts in the Peruvian sector, yet a small number of depletions, indicating a real lack of events and not a statistical artifact.

In the morningside, depletions tend to occur above the Pacific and the Atlantic-African sectors. Instead, the depletion activity is clearly less common in the Indian sector. In the morningside we cannot use the Tsunoda mechanism for explaining the longitude dependence of the depletions, because the sunset in conjugate $E$ layers does not affect the postmidnight sector. Recently, Scherliess and Fejer [1999] found that the equatorial $F$ region vertical drifts show largest longitudinal variations during high solar flux periods, particularly during the solstices. The morningside depletions were approximately detected during northern winter and summer and during high solar flux periods, indicating that the favorable nighttime velocity profiles could explain the longitudinal dependence of morningside depletions.

One can conclude that the differences between Figure 8c and Figure 11c are due to the seasonal-longitudinal dependence [Tsunoda, 1985] of the eveningside depletions, because morningside depletions do not depend on the season and longitude in the same way that the eveningside depletions do. First, the lack of events in the Indian sector in Figure 11c confirms that the Indian depletions in the evening panel are due to the seasonal-longitudinal effect. Second, there are only a few eveningside events in the Pacific, whereas the morningside depletions have their highest probability of occurring there. This confirms that the lack of evening events in the Pacific sector is indeed a seasonal-longitudinal effect. Third, the depletion probability in the Atlantic-African sector is high in both panels and in
all seasons, suggesting that the depletion activity in the eveningside is not a seasonal-longitudinal effect in this area but has to be explained by some other mechanism. This might also be true of the South American sector (at -60° to -30° longitudes), which shows noticeable occurrence rates in the eveningside and in the morningside.

We suggest that the longitude, in general, has more impact on the generation of eveningside depletions than the global magnetic activity. Comparing the eveningside normalized $K_p$ and longitude distributions, we see that higher probabilities are observed in the longitude histogram than in the $K_p$ histogram. In the morningside this suggestion is not as obvious.

6. Summary

When comparing the equatorial density depletions encountered by the DE 2 satellite in the eveningside (1900-2300 MLT) and morningside (2300-0600 MLT), the most remarkable result is that their occurrence rates depend differently on magnetic activity. In the period of 1981-1983, when the solar flux was high, the eveningside depletions (observed during spring and late fall) and morningside depletions (observed during winter and summer) vary with global magnetic activity in such a way that the following two general conclusions can be made:

1. In the eveningside (1900-2300 MLT), the DE 2 results suggest that the occurrence rate of equatorial $F$ region depletions decreases with increasing global magnetic activity with a 2-hour time delay. For time delays of less than 2 hours the depletion occurrence rate does not depend on magnetic activity, whereas some inverse correlation is observed with time delays of more than 2 hours.

2. In the morningside (2300-0600 MLT), the occurrence rate of equatorial $F$ region depletions increases instantly with $K_p$ index, although the best correlation is observed with a 2-hour delay. Weak correlation is observed with time delays of 3-4 hours, whereas magnetic activity does not appear to affect anymore 5-6 hours after the substorm onset. For time delays of more than 6 hours, a weak correlation appears again.

The longitude dependence of depletions can be attributed to both season and longitude. In the eveningside the seasonal-longitudinal dependence can be partly explained in terms of Tsuruda [1985], and the results are also consistent with recent work of McClure et al. [1998]. In the morningside the seasonal-longitudinal dependence might be related to the favorable nighttime velocity drifts that depend on season, longitude, and solar flux [Scherliess and Fejer, 1999]. The additional conclusions of this study therefore are as follows:

3. The eveningside density depletions tend to occur everywhere except above the Pacific during equinox months, although there is one significant peak of occurrence at longitudes of -120° to -90°. With the exception of the peak, the longitudinal dependence of eveningside depletions is consistent with previous studies.

4. In the morningside near solstice, we found that the depletions prefer to develop over the Pacific and the Atlantic-African sectors, whereas low occurrence probabilities are observed in the Indian sector.

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