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L. Scherliess¹, B. G. Fejer¹, J. Holt², L. Goncharenko², C. Amory-Mazaudier³, and M. J. Buonsanto²,⁴

Abstract. We use incoherent scatter radar measurements from Millstone Hill and Saint Santin to study the midlatitude F region electrodynamic plasma drifts during geomagnetically quiet and active periods. We present initially a local time, season, and solar flux dependent analytical model of the quiet time zonal and meridional ExB drifts over these stations. We discuss, for the first time, the Saint Santin drift patterns during solar maximum. We have used these quiet time models to extract the geomagnetic perturbation drifts which were modeled as a function of the time history of the auroral electrojet indices. Our results illustrate the evolution of the disturbance drifts driven by the combined effects of prompt penetration and longer lasting perturbation electric fields. The meridional electrodynamic disturbance drifts have largest amplitudes in the midnight-noon sector. The zonal drifts are predominantly westward, with largest amplitudes in the dusk-midnight sector and, following a decrease in the high-latitude convection, they decay more slowly than the meridional drifts. The prompt penetration and steady state zonal disturbance drifts derived from radar measurements are in good agreement with results obtained from both the ion drift meter data on board the Dynamics Explorer 2 (DE 2) satellite and from the Rice Convection Model.

1. Introduction

The midlatitude ionospheric plasma drifts can be simultaneously driven by several electric field sources. The two most important ones are the ionospheric wind dynamo and the direct penetration of high-latitude convection electric fields into the plasmasphere. The ionospheric wind dynamo generates electric fields through the dynamo action of the thermospheric wind circulation driven by solar heating and during geomagnetic active periods, also by thermospheric disturbance winds driven by enhanced Joule heating in the auroral regions [Blanc and Richmond, 1980; Mazaudier et al., 1987; Mazaudier and Venkateswaran, 1990; Scherliess and Fejer, 1997]. Prompt penetration electric fields can affect the midlatitude plasma drifts nearly instantaneously during transient periods of insufficient shielding by plasma sheet currents [Jaggi and Wolf, 1973] and also during periods of strong steady auroral convection.

Over the last two decades, incoherent scatter radar observations have been used extensively to study the midlatitude ionospheric electrodynamic (ExB) plasma drifts during geomagnetically quiet and disturbed periods. Blanc and Amayenc [1979] have used incoherent scatter radar observations during geomagnetically quiet days over Saint Santin during the 1973-1975 solar minimum period to derive an analytical seasonal model of their quiet time F region plasma drifts. This model included a steady drift component and the first four diurnal harmonic oscillations. Wand [1981] has used Millstone Hill observations during May 1976 to November 1977 to analytically model the upper midlatitude solar minimum electrodynamic plasma drifts for geomagnetically quiet and disturbed plasma drifts. The disturbance drifts were modeled as a function of the Kp index. Buonsanto et al. [1993] have used a significantly larger database of Millstone Hill plasma drift observations comprising 73 experiments from February 1984 to February 1992 and determined the average seasonal quiet time plasma drift patterns for both solar minimum and maximum conditions. The characteristics of equatorial, low-latitude, and midlatitude plasma drifts measured with incoherent scatter radar were reviewed by Richmond [1995]. More recently, Buonsanto and Witasse [1999] presented an updated study of the local time, season, solar cycle, and geomagnetic activity dependent climatologies of the Millstone Hill F region plasma drifts and thermospheric winds. In this study, magnetic activity effects were again accounted for as a function of the Kp index.
A detailed study of the middle- and low-latitude F region zonal plasma drifts measured by the Ion Drift Meter (IDM) on board the polar orbiting Dynamics Explorer 2 (DE 2) satellite during the 1981-1983 solar maximum period was presented by Heelis and Coley [1992]. They derived the average latitudinal plasma drift patterns during geomagnetically quiet and disturbed periods corresponding to $Kp \leq 2.0$ and $Kp \geq 3.0$, respectively. They could not derive the seasonal dependence of these drifts since the DE 2 measurements had season and local time interlocked.

Recently, Fejer and Scherliess [1995] have introduced a new methodology which was able to separate, for the first time, the effects of different electric field sources on the plasma drifts during geomagnetic active periods. Scherliess and Fejer [1998] and Fejer and Scherliess [1998] have used this methodology to analytically model the temporal and latitudinal variations of the low- and middle-latitude F region zonal perturbation drifts measured by the DE 2 satellite during geomagnetically disturbed periods as a function of the time history of the hourly averaged $AE$ indices. They determined the drift patterns owing to transient prompt penetration electric fields and of longer lasting disturbances (time constants longer than a few hours) because of the combined effects of ionospheric disturbance dynamo electric fields and leakage of high-latitude electric fields to lower latitudes.

We have used extensive incoherent scatter radar observations from Millstone Hill and Saint Santin to study midlatitude F region zonal and meridional plasma drifts during geomagnetic quiet and active conditions. We initially present a comprehensive summary of the local time, seasonal, and solar cycle variations of the quiet time drifts over these two midlatitude stations. This includes, for the first time, the seasonal dependence of the average solar maximum plasma drifts over Saint Santin. The main focus of this work is the study of the temporal evolution of the midlatitude plasma drifts during geomagnetic active periods using the methodology introduced by Fejer and Scherliess [1995]. We have used our quiet time drift model to determine the disturbance drifts which were then modeled as a function of the $AE$ index.

In the following sections, we will first briefly review the radar measurement techniques and describe our data analysis. Then we present our quiet time model, describe the storm time dependent disturbance drift patterns and compare them with results from earlier studies.

2. Measurement Techniques and Data Analysis

The Millstone Hill radar (42.6°N, 288.5°E, Apex magnetic latitude 54°) measures the line-of-sight plasma drift velocity from the Doppler shift of the 440 MHz backscatter signal. The three-dimensional drift velocity over the radar site is obtained from measurements in three directions and with the assumption of a uniform velocity field [e.g., Buonsanto et al., 1993; Buonsanto and Witasse, 1999]. The measurements in our database correspond to an altitude of 300 km, have a typical error of ~8 m/s, and a cycle time of ~1 hour. We will use here drift components perpendicular to the Earth magnetic field. In the $F$ region over Millstone Hill, a plasma velocity of 22 m/s corresponds to an electric field of 1 mV/m.

The Saint Santin incoherent scatter radar site (45°N, 2°E, 40° magnetic latitude) operated originally on a bistatic mode with a transmitter in Saint Santin and a receiver at a distance of 302 km in Nancay. In 1973, two additional receivers were installed in Monpazier and Mende (~100 km from the transmitter site), allowing for the determination of three-dimensional ion drift vectors at a typical height of ~300 km [Bauer et al., 1974]. The measurement error was of the order of 5-10 m/s and the integration time was ~30 min. The Saint Santin radar operated until 1986. Over Saint Santin, a plasma velocity of 25 m/s in the $F$ region corresponds to an electric field of 1 mV/m.

We have used 15 years of Millstone Hill incoherent scatter radar observations from 1978 to 1992, comprising more than 4500 hours of plasma drift observations, which have been recently reanalyzed. We have also used 14 years of plasma drift observations from the Saint Santin incoherent scatter radar from 1973 to 1986 which were extracted from the National Center for Atmospheric Research Coupling, Energetics and Dynamics of Atmospheric Regions (NCAR CEDAR) database. We discarded Saint Santin late afternoon and nighttime drift observations (1600-0700 LT) obtained between September 1981 and March 1982 owing to unexpectedly large nighttime drifts (westward velocities exceeding 200 m/s, even during geomagnetically quiet periods). The reason for these large drifts is unknown to us. The average values of the solar decimetric flux indices for the Millstone Hill and Saint Santin data sets are 140 and 125, respectively. The number and dates of the Millstone Hill and Saint Santin experiments used in this study can be obtained from the NCAR CEDAR database.

2.1. Quiet Time Analysis

We have used these data to determine empirical analytical models for both the quiet time and disturbance plasma drifts over these midlatitude stations. For our quiet time plasma drift models, we have included only data with a current 3-hour magnetic index $Kp$<3.0 ($Kp$ ~1.8). We will discuss later the implications of this relatively relaxed quiet time criterion.

The electrodynamic components of the plasma drifts (perpendicular/eastward and perpendicular/northward to $B$) were modeled as:

$$v(t, d, S_a) = \sum_{i=1}^{8} \sum_{k=1}^{6} a_{i,k} f_k N_{i,k}(t)$$

(1)
tween our 4-month seasons. This interpolation provides a reasonably realistic transition between seasons.

A range of 4-15 days was employed for the transition because even an unweighted fit leads to essentially the same model restriction to our Millstone Hill storm time analysis to moderately disturbed periods, i.e., to periods when the

Finally, a simple linear interpolation scheme over a range of ±15 days was employed for the transition between our 4-month seasons. This interpolation provides a reasonably realistic transition between seasons.

2.2. Storm Time Analysis

As mentioned above, our quiet time model drifts correspond to an average $Kp$ index of ~1.8. In the next step, we have determined the perturbation drift patterns during geomagnetic active periods and their storm time evolution. To extract the perturbation drifts out of the data set, we have subtracted the season and solar cycle dependent average quiet time drifts, using our new empirical quiet time models, from the measured drifts (for a detailed description see Fejer and Scherliess [1997]). The resulting perturbations are due to storm time generated electric fields and also to the day-to-day variability of the ionospheric dynamo electric fields.

Since during large nighttime storm periods, Millstone Hill can be in the auroral zone, we have excluded plasma drift observations when the maximum $Kp$ index over the preceding period of 6 hours was above 5.0. This criterion restricts our Millstone Hill storm time analysis to moderately disturbed periods, i.e., to periods when the equatorward edge of the shielding layer is poleward of the radar site. We further minimized the inclusion of auroral drifts, and also of unusually large drifts (associated with subauroral ion drifts (SAIDs), for example) into our database, by limiting the magnitudes of the perturbation drifts to values smaller than 150 and 80 m/s for the zonal and perpendicular/northward drift component, respectively.

Following the procedure described by Scherliess and Fejer [1998], we have characterized the level of enhanced high latitude geomagnetic activity, using modified hourly averaged auroral electroject (AE$_d$) indices, with $AE_d = AE - 160$ nT. For the time period prior to July 1988, we have used the standard AE index based on measurements from 12 auroral stations and, for the later period, a provisional index based on 11 stations. For the second half of 1988 and also for 1989 (with the exception of March) AE$_d$ indices are not available, and, consequently, data from this period have not been used in our perturbation drift analysis. The AE$_d$ index has been empirically related to both the polar cap cross potential and to the hemispheric high-latitude energy input [Ahn et al., 1983, 1992]. This allows us to compare our empirical disturbance patterns with results from global convection models.

For each radar station the ionospheric perturbation drift components were expressed as

$$v(t) = \sum_{i=1}^{6} \left[ a_{i,1} \Delta AE(t - 30 \text{ min}) + a_{i,2} \Delta AE(t - 90 \text{ min}) + a_{i,3} AE_d(1 - 3 \text{ hour}) + a_{i,4} AE_d(4 - 9 \text{ hour}) \right] N_i(t). \tag{2}$$

The first two terms under the summation resemble the parametrization used by Scherliess and Fejer [1998] to account for prompt penetration drifts related to changes in the auroral current systems with average time delays of 30 and 90 min, respectively. To account for longer lasting drift perturbations, which have been parameterized by Scherliess and Fejer [1998] by an average of $AE_d$ indices over the past nine hours, we have instead used two separate parameters, i.e., the average of $AE_d$ indices over the past 1-3 hours and the average over the past 4-9 hours. This parametrization significantly improves the temporal evolution of the longer lasting perturbations and provides a better representation of the perturbation drifts during the initial hours of geomagnetic active periods. After several hours of auroral activity, however, this parametrization gives essentially the same results as presented by Scherliess and Fejer [1998]. The limitations of the use of the $AE_d$ indices in our analysis were discussed by Fejer and Scherliess [1997, 1998]. Our empirical models, based on the $AE_d$ index, do not take into account some potentially important processes and average out the effects of a number of ionospheric and magnetospheric processes that could play important roles on the magnitude and phase of...
the electric field perturbations as well as on the shielding time constants. For example, results presented by Foster et al. [1986] suggest that IMF $B_y$ might cause large changes in the perturbation electric fields over Millstone Hill. A comprehensive study of these additional processes requires a significantly larger database than currently available.

In summary, we have developed individual empirical analytical models for the Millstone Hill and Saint Santin electrodynamical plasma drifts for geomagnetically quiet and disturbed periods. These models include the seasonal and solar cycle variations of the quiet time drifts as well as short-term and longer lasting perturbation drifts during geomagnetically disturbed periods. Combined, these models can describe the average mid-latitude plasma drifts during various geomagnetic conditions.

3. Results and Discussion

In this section we will discuss briefly our solar minimum and solar maximum average quiet time drift patterns obtained from our Millstone Hill and Saint Santin models. Then we will describe our disturbance drift patterns and compare them with other observations and also with predictions from global convection models.

3.1. Quiet Time Electrodynamic Drifts

Figure 1 shows the average seasonal quiet time patterns for the perpendicular/northward plasma drift component over Millstone Hill for low and high solar flux conditions. The data have been divided into summer (May-August), equinox (March, April, September, October), and winter (November-February). The average decimetric solar flux indices are $S_a = 85$ for the low solar flux intervals and $180$, $200$, and $190$, for summer, winter, and equinox high solar flux periods, respectively. The standard deviation of our average drifts is between $\pm 20$ and $40$ m/s. The average number of samples per bin is $\sim 20$, resulting in standard errors of the mean between $\sim 5$ and $10$ m/s. Figure 1 indicates that the perpendicular/meridional drifts are northward in the early morning and prenoon sector and southward at the later times, with a return to the northward direction in the late afternoon during low solar flux summer and equinox conditions. The northward morning drifts reach maximum values between $\sim 20$ and $30$ m/s, and the afternoon southward drifts have maximum values of $\sim 10$ m/s. Although, large solar cycle variations are observed in the perpendicular/northward drift component (e.g., equinox early morning), no significant systematic effects are evident. The results in Figure 1 are
in good agreement with the average drift patterns reported by Buonsanto et al. [1993] and Buonsanto and Witasse [1999], who discussed their main characteristics and large day-to-day variability. The latter work also reported differences between the vernal and autumnal drift patterns, which were most pronounced in the early morning to noon period. These effects are not being accounted for in our current study.

The thick solid lines in Figure 1 represent our quiet time model predictions, which have been calculated using (1) for each data point and binned and averaged the same way as the observations. As expected, our model results are in good agreement with the average drift patterns with typical fluctuations of ~1-5 m/s. Systematic discrepancies between model and data are observed only during low solar flux winter afternoon conditions when the empirical model underestimates the equatorward/ downward drift velocities. These differences are largely due to our use of a linear solar cycle variation in our empirical model.

Figure 2 shows the average perpendicular/northward quiet time plasma drifts over Saint Santin for solar minimum and maximum conditions and the corresponding empirical model results. The average solar flux values for summer, winter, and equinox are ~85, 75, and 75 for the low solar flux data and 180, 205, and 180 for the high solar flux data. The average $K_p$ index is again ~1.8 with slightly larger values during summer and equinox high solar flux conditions. The Saint Santin drifts resemble many of the features observed over Millstone Hill, with northward drifts in the prenoon sector and southward drifts in the afternoon. In general, the solar minimum results shown in Figure 2 exhibit strong semidiurnal oscillations and closely resemble the solar minimum patterns presented earlier by Blanc and Amayenc [1979] who used 3 years of drift observations. However, they reported large downward/southward drifts during December solstice nighttime periods, whereas our corresponding results indicate upward/northward drifts.

The Saint Santin northward drifts show strong semidiurnal patterns near solar minimum and diurnal type variations during solar maximum. Saint Santin solar maximum drifts have not been studied earlier, and therefore ours is the first model representation for these drifts. Figure 2 indicates that from ~0800 to 1400 LT, the equinoctial drifts do not change significantly with the phase of the solar cycle, whereas the solstitial data show opposite variations with an increase in the northward drifts in the summer data and a decrease in the winter. The relatively large southward drifts in the morning from ~0400 to 0800 LT and in the afternoon from ~1400 to 1800 LT drastically decrease with

Figure 2. Same as Figure 1, but for Saint Santin.
increasing solar flux during equinox and summer and even reverse toward the northward direction in the June solstice morning sector.

It is not clear if the December solstice drift pattern is entirely realistic or biased by instrumental offsets. First of all, the December solstice daytime and nighttime drifts are significantly different from the equinoctial values. In addition, as pointed out by Takami et al. [1996], the nighttime Saint Santin winter drifts should be strongly affected by the corresponding conjugate summer ionosphere, which lies at a geographic latitude of 31°S. Therefore we would expect a close similarity between the Saint Santin December solstice and the Shigaraki (35°N dip latitude) June solstice nighttime drifts measured by the MU radar [Takami et al., 1996]. However, the June solstice solar maximum nighttime average drifts measured by this radar show southward drift velocities of only ~5 - 10 m/s, which would suggest a DC bias. Clearly, our solar maximum December solstice Saint Santin drifts should be considered with a high degree of caution.

The seasonally averaged Millstone Hill eastward drift pattern for geomagnetically quiet conditions are shown in Figure 3. The data are again shown for low and high solar flux conditions with the same average solar flux values given for the northward component. The zonal drifts over Millstone Hill are westward at night with maximum values of ~60 m/s in winter and 40 m/s in summer. During daytime, and particularly around noon, the zonal drifts have eastward amplitudes with largest magnitudes (up to 35 m/s) during equinox. During summer, the average zonal drifts are always westward. The standard deviation is between ~25 and 50 m/s, indicating large quiet time variability. We will show later that some of this variability was introduced by the choice of our quiet time binning criterion. The thick solid lines in Figure 3 represent again the predictions of our quiet time model. Generally, the zonal plasma drifts at Millstone Hill tend to be more westward at night and more eastward during the day with increasing solar flux, although, systematic variations are relatively small (of the order of 10 m/s). These results are also consistent with those from earlier studies [Buonsanto et al., 1993; Buonsanto and Witasse, 1999].

Figure 4 shows the average seasonal solar minimum and maximum quiet time zonal drift patterns over Saint Santin. The average solar flux indices are the same as for Figure 2. The solar minimum drift patterns are in good agreement with the results of Blanc and Amayenc [1979], with the exception of the summer early night-
time drifts for which their study indicated a westward drift reversal which is not seen in our results based on a significantly larger data set. The Saint Santin zonal drifts vary significantly with the phase of the solar cycle. The nighttime drifts increase from \(\sim 20-30\) m/s to \(\sim 40-80\) m/s between our low and high flux conditions.

Figure 5 shows the combined winter and equinox average solar cycle variation in the early nighttime period. In this case, we have used solar flux bins of 30 units for indices between 60 and 210 and a single bin for larger values. The vertical bars indicate the standard deviation in each bin, and the solid line is our empirical model representation. These drifts increase linearly with increasing solar flux at a rate of \(\sim 40\) m/s per 100 flux units. The solar cycle variations during summer are \(\sim 50\%\) smaller.

Zonal plasma drift observations at Jicamarca (12°S geographic, magnetic latitude 1°N) [Fejer et al., 1991], Arecibo (18°N geographic, magnetic latitude 30°N) [Fejer, 1993], and from the IDM onboard the DE 2 satellite [Scherliess, 1997] indicate increasing solar cycle variations with decreasing latitude, in good agreement with the observed solar cycle dependence at Millstone Hill and Saint Santin. It is interesting to note that solar cycle variations at Arecibo are smallest during December solstice, when the ionospheric dynamo in the conjugate hemisphere, which is located at a significantly larger geographic latitude (45°S), largely determines the Arecibo nighttime plasma drifts [Fejer, 1993; Takami et al., 1996]. The conjugate point of Saint Santin, however, lies at a lower latitude (18°S) than this station. Therefore, as expected, the solar cycle variations of the Saint

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**Figure 4.** Same as Figure 3, but for Saint Santin.

**Figure 5.** Solar cycle variation of the equinox and winter early night Saint Santin zonal drifts.
Santin zonal drifts are smallest in the summer, when they are determined mostly by the dynamo action in the local hemisphere. The quiet time model described above allowed us to determine the perturbation drifts which were used in the storm time study presented in section 3.2. As we will see, high-latitude electric fields affect the low-latitude plasma drifts with decreasing amplitudes toward the equator, even under quasi-stationary conditions. Therefore, for a given quiet time criterion (based on the Kp index, for example), we expect our quiet time drifts to have latitudinally increasing contributions due to electric fields of high-latitude origin. Figure 6 shows that the zonal disturbance drifts over Millstone Hill have significant amplitudes even for Kp < 3 (Kp = 1.8). In this case Figure 6 (top) was obtained by binning the yearly averaged Millstone Hill zonal drifts for geomagnetically quiet (average 6-hour Kp<3.0) and extremely quiet (average 6-hour Kp<1.3) conditions, and Figure 6 (bottom) shows the difference of the two curves and the results obtained from our disturbance model. The scatterbars indicate the variability of the extremely quiet drifts (Kp = 0.7) corrected for seasonal and solar cycle effects. Under the same conditions, the amplitudes of the Santin zonal disturbance drifts are about a factor of two smaller than over Millstone Hill. The effects of the steady state leakage of high-latitude zonal electric fields, which drive perpendicular northward disturbance drifts, are essentially negligible for Kp < 3 even over Millstone Hill.

### 3.2. Midlatitude Disturbance Plasma Drift Patterns

Figure 7 shows an idealized storm scenario with an increase of the AE index by 300 nT above our quiet time value of 130 nT during a period of 9 hours. Figure 8 presents the Millstone Hill disturbance drift patterns for the storm times defined in Figure 7. The data and the scatterbars were obtained by binning and averaging the data for the conditions in Figure 7 and smoothed by a three-point running average. The average values for the parameters defined in (2) are given in Table 1. The solid curves present the results from our empirical analytical model obtained from (2). It is important to note that our data binning can only approximately reproduce the idealized storm scenario and that it does not completely separate the responses of the prompt penetration and disturbance dynamo processes. In spite of these limitations, the binned data is generally in good agreement with the results from our simultaneous multiparameter fitting procedure and, as we will see later, also with theoretical patterns obtained from the Rice Convection Model (RCM).

Figure 8 indicates that at time t0, following an increase in the AE index by 400 nT, the prompt penetration zonal electric fields drive perpendicular northward drifts during the day and larger amplitude southward

### Table 1. Average Storm Time Parameters

<table>
<thead>
<tr>
<th>Storm Time</th>
<th>t0</th>
<th>t1</th>
<th>t2</th>
<th>t3</th>
<th>t4</th>
<th>t5</th>
<th>t6</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔAE(t - 30 min) (nT)</td>
<td>243</td>
<td>-33</td>
<td>-58</td>
<td>-34</td>
<td>-225</td>
<td>-41</td>
<td>11</td>
</tr>
<tr>
<td>ΔAE(t - 90 min) (nT)</td>
<td>48</td>
<td>209</td>
<td>-27</td>
<td>-29</td>
<td>46</td>
<td>-230</td>
<td>-7</td>
</tr>
<tr>
<td>AEΩ(1-3 hour) (nT)</td>
<td>24</td>
<td>149</td>
<td>293</td>
<td>287</td>
<td>271</td>
<td>249</td>
<td>30</td>
</tr>
<tr>
<td>AEΩ(4-9 hour) (nT)</td>
<td>60</td>
<td>79</td>
<td>89</td>
<td>275</td>
<td>126</td>
<td>141</td>
<td>165</td>
</tr>
</tbody>
</table>
Figure 8. Average perpendicular northward and eastward disturbance drifts over Millstone Hill for the conditions and storm times shown in Figure 7. The solid lines indicate the patterns from our disturbance model, and the dashed lines at storm times $t_2$ and $t_3$ were obtained using the parametrization of Scherliess and Fejer [1998]. The scatter bars denote the standard error of the means.
drifts at night with a maximum value of $\sim 25$ m/s at 0400 LT. The initial time response of the meridional electric fields generates a small eastward disturbance drift in the early morning-noon period and larger westward drifts at other local times. The largest initial time westward drift perturbation is $\sim 40$ m/s, and it occurs near dusk. As stormtime increases, the disturbance drifts initially decrease in amplitude and shift to later local times but do not change much after $\sim 2$ hours of continuous magnetic activity, as shown by the patterns at storm times $t_2$ and $t_3$.

Storm time $t_4$ (Figure 8) shows the disturbance patterns resulting from the sudden decrease in the $AE$ by 400 nT. In this case, the nighttime perturbation drifts change from the downward/southward direction to upward/northward, and the prenoon downward/southward drifts are further increased. The most noticeable changes in the zonal drifts occur before noon when they become westward. These perturbation drifts are again due to the combined effects of large transient prompt penetration drifts (with opposite sign to those for storm time $t_4$ in Figure 8) and longer lasting time-delayed disturbances. The agreement between the averaged data and our model predictions (solid line) is very good, but a phaseshift of roughly 1-2 hours in the prompt penetration response toward later local times for both components would make the agreement even better. It is interesting to note that Blanc [1983] has noted that a similar phaseshift would also bring the Saint Santin drift data in closer agreement with his model results.

One hour after the decrease of the $AE$ index, at storm time $t_5$, the meridional perturbation drifts have significantly smaller amplitudes. The zonal drifts, however, still exhibit large nighttime westward perturbations, and small eastward perturbations around sunrise. Storm time $t_6$ (Figure 8) shows that after 6 hours of quieting, the perpendicular/northward drift perturbations have largely returned to their quiet time level, but the zonal drifts still display large westward perturbations in the evening sector, which are not fully captured by our current model. This suggests that other disturbance mechanisms or drift perturbations with different timescales than considered in our model might be operating during the recovery phase.

The smaller database of drift measurements from Saint Santin did not allow us to determine their stormtime dependence in as much detail as given in Figure 8. However, as will be shown below, we were still able to capture the basic features of their prompt penetration and longer lasting disturbance drift patterns.

Scherliess and Fejer [1998] and Fejer and Scherliess [1998] have used extensive ion drift meter data from the DE 2 satellite to determine the middle- and low-latitude ionospheric zonal disturbance drift patterns. Figure 9 (top) shows the good agreement between the Millstone Hill prompt penetration zonal drifts at storm times $t_0+30$ min and $t_0+90$ min and the corresponding DE 2 drifts for an average invariant latitude of 55°.

It is important to note that the DE 2 results were derived from longitudinally averaged measurements. Figure 9 (bottom) compares the Saint Santin results and the corresponding DE 2 results. Fejer and Scherliess [1998] pointed out that in the postmidnight-morning sector, the DE 2 initial time disturbance drifts change noticeably for invariant latitudes from 45° to 35°. Figure 9 shows that surprisingly the Saint Santin initial time disturbance pattern is in better agreement with the DE 2 results for an average invariant latitude of 35° than for $\Lambda = 45°$. Fejer and Scherliess [1998] suggested that the large change of the DE 2 initial zonal disturbance drift patterns from 45° to 35° was due in part to the larger uncertainties resulting from the large decrease in the number of postmidnight measurements at lower latitudes. The Saint Santin results suggest that this argument is questionable. The $t_0+90$ min DE 2 and Saint Santin disturbance drift patterns are in good agreement, although the radar data show larger westward drifts in the dusk to early night period.

Figure 10 shows the Millstone Hill and Saint Santin and DE 2 disturbance patterns after an increase in the $AE$ index by 400 nT over a period of 9 hours. The radar drifts are again consistent with the satellite drifts but have systematically larger magnitudes, in particular during the dusk to early nighttime hours. However, we
have to reiterate here that the DE 2 results represent longitudinally averaged patterns and have season and local time locked together (the early nighttime period, for example, corresponds to equinoctial conditions).

4. Comparison With Theoretical Models

The penetration of high-latitude electric fields to middle, low, and equatorial latitudes has also been investigated using several global convection models [e.g., Spiro et al., 1981, 1988; Senior and Blanc, 1984; Zakharov et al., 1989; Fejer et al., 1990; Peymirat and Fontaine, 1994; Peymirat, 1998; Tsunomura, 1999]. These models calculate the global ionospheric electric fields and currents by solving the continuity equation for ionospheric currents for a given high-latitude electrostatic potential or the field-aligned current distribution on a two-dimensional (thin shell) ionosphere with given ionospheric conductances. The middle- and low-latitude perturbation electric fields obtained from different models are similar since they depend mostly on the high-latitude potential penetrating to lower latitudes and on the ionospheric conductances and not on the details of magnetospheric processes. The most comprehensive theoretical prompt penetration results have been provided by the RCM which accounts for the coupled electrodynamics of the inner magnetosphere and ionosphere [e.g., Wolf et al., 1986; Spiro et al., 1988]. The local time and latitude zonal and meridional perturbation electric fields predicted by the RCM were studied by Fejer et al. [1990]. We can compare their results with the radar disturbance drift patterns presented above by using the empirical relationship between the polar cap potential drop and the $AE$ index derived by Ahn et al. [1992], i.e., $\Phi (kV) = 36 + 0.082 AE_{12}(nT)$, where $AE_{12}$ is the auroral electrojet index using 12 stations. In this case, a change in the $AE$ index by 400 nT corresponds to a change in the cross polar cap potential of $\sim 33$ kV.

Figure 11 shows the comparison of the Millstone Hill and Saint Santin prompt penetration drift patterns and the RCM results for an increase in the polar cap potential of $33$ kV. These RCM patterns, which correspond to run C of Spiro et al. [1988], were discussed in detail by Fejer et al. [1990] and compared to DE 2 model results by Fejer and Scherliess [1998]. Figure 11 indicates that the initial time response of the Millstone Hill drifts is in good agreement with the RCM results. Notice that the drift amplitudes decrease and shift to later local times as the plasma sheet inner edge adjusts to the new cross polar cap potential. The Saint Santin perpendicular meridional disturbance drifts are in general agreement with the model results, whereas the zonal drifts near dusk are noticeably larger. Fejer and Scherliess [1998] have pointed out that these RCM quasi steady state drifts underestimate the DE 2 zonal disturbance drifts for latitudes $\Lambda \leq 45^\circ$ consistent with our results. The results above indicate that the radar and DE 2 perturbation drift patterns are in reasonably good agreement. They are also generally consistent with the predictions from the RCM, as well as from other global convection models.

5. Summary and Conclusions

We have used incoherent scatter radar observations from Millstone Hill and Saint Santin to study the characteristics of the average midlatitude quiet time and disturbance electrodynamic plasma drifts. Our quiet time Millstone Hill drift patterns are in good agreement with earlier studies based on smaller databases. The Saint Santin quiet time measurements were used to determine, for the first time, the seasonal variations of these drifts for both low and high solar flux conditions. The Saint Santin evening zonal drifts increase with solar flux, whereas the corresponding Millstone Hill drifts are essentially solar flux independent.

We have modeled the Millstone Hill and Saint Santin disturbance drifts obtained by removing from each measurement the season and solar flux dependent quiet time values. These stormtime dependent perturbation drifts were used to study and model, for the first time, the temporal evolution of the prompt penetration and longer lasting zonal and meridional $E \times B$ disturbance drifts. The radar disturbance patterns are in good agreement with results derived from zonal drift measurements by the DE 2 satellite. This, and also earlier studies, also indicates that the RCM, as well as other detailed convection models, can reproduce the average disturbance drift patterns with reasonable accuracy.

The present empirical model provides a relatively simple description of the time dependent evolution of the midlatitude disturbance drifts based on the history of the $AE$ index. A copy of the current model can be obtained from the authors. The major challenge for the next few years lies in the understanding of the large variability of these disturbance patterns.
Figure 11. Comparison of the disturbance drift patterns obtained from our Millstone Hill and Saint Santin models with results from the Rice Convection Model (RCM) for an increase in the polar cap potential drop by 33 kV. Here the RCM initial time responses correspond to a time \((t_0 + \epsilon)\) immediately after the change in \(\Phi\) (short-dashed line) and 10 min later (long-dashed line).
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