Delayed ionospheric effects of the geomagnetic storms of March 22, 1979 studied by the sixth co-ordinated data analysis workshop (CDAW-6)

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ABSTRACT. The Saint-Santin (45° N, 2° E) quadristatic radar observations of E and F region meridional winds, $\mathbf{E} \times \mathbf{B}$ drifts in the F region and height-integrated ionospheric currents are presented along with ground magnetic variations from three equatorial stations to indicate the nature of the global ionospheric and thermospheric perturbations that persisted on March 23, 1979 with a time delay of several hours after the magnetospheric substorm events of March 22. An attempt is made to interpret and co-ordinate these events qualitatively in terms of the disturbance dynamo theory of Blanc and Richmond (1980). However, a quantitative two-dimensional modelling of the events is singularly unsuccessful, probably because the high-latitude heat source from this storm could not be parameterized adequately as a function of the auroral activity indices.

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1. INTRODUCTION

Several aspects of the geomagnetic storm that started with a sudden commencement or impulse at 0826 UT on March 22, 1979 and was followed by two substorm events on that day have been reported in the literature (McPherron and Manka, 1985). Some of these studies (Roble *et al.*, 1987 ; Senior and Blanc, 1987) have been concerned with the ionospheric consequences of the substorm-induced convection electric fields of magnetospheric origin. Taieb and Poinsard (1984), on the other hand, concentrated on changes in the ionospheric electron densities and electron and ion temperatures, as observed by the Saint-Santin radar, on the day of the storm and for a few days both before and after the storm.

The purpose of the present communication is to report Saint-Santin radar observations of meridional neutral wind velocities in the E and F regions of the ionosphere, the $\mathbf{E} \times \mathbf{B}$ drifts in the F region and the height-integrated ionospheric currents on March 23, 1979. The observations reveal that there are disturbances occurring in all these parameters which are quite distinct in character from the disturbances associated with the main storm events of the previous day. Moreover, the middle latitude ionospheric disturbances on March 23 are found to be accompanied by equatorial magnetic field disturbances whose characteristics are also markedly different from the magnetic field disturbances on the day of the main storms. An attempt is made in this communication to show that the global disturbances of March 23 can be coordinated and understood on the basis of the disturbance dynamo theory of Blanc and Richmond (1980), at least in a qualitative fashion. We have had no success, however, in the numerical simulation of the disturbances using a two-dimensional numerical model.

The organization of the rest of this communication consists of a brief description of the time evolution of events of March 22 and 23 in Section 2 ; an account of observations of the various parameters in Sections 3-6 ; a brief description of the Blanc-Richmond disturbance dynamo theory in Section 7 ; and a qualitative comparison of the specific predictions of the theory with observations in Section 8.

2. TIME EVOLUTION OF STORM EVENTS

Figure 1 traces the time evolution of the geomagnetic storm events of March 22 and March 23, 1979, as indicated by variations in the z-component of the interplanetary magnetic field (IMF) and the AL and AU auroral electrojet indices. This figure shows that after a fairly quiet period on the previous day, the

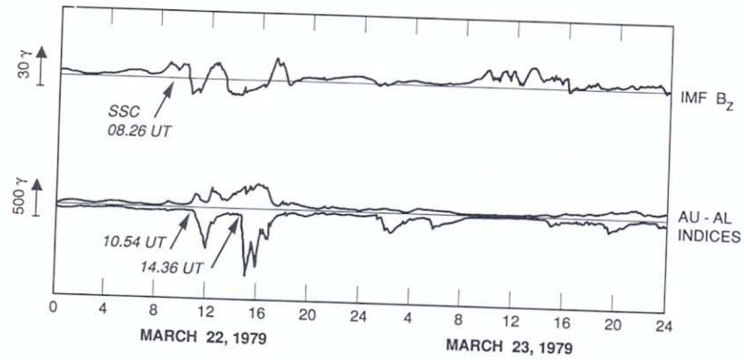

Figure 1

The progress of the storm on March 22 and March 23, 1979, as indicated by B_z, the z-component of the interplanetary magnetic field (IMF) *in the top panel and the AU and AL auroral indices, above and below the base line, respectively, of the bottom panel.*

storm was initiated with a sudden impulse at 0826 UT on March 22, and is followed by the onset of two substorms, one at 1054 UT and the second at 1436 UT (McPherron and Manka, 1985). The substorm events are clearly marked in the auroral indices and are correlated with the southward excursions of the IMF, lasting 70 and 180 min, respectively. Subsequent to the substorms, there are minor disturbances in the *AL*-index around midnight associated with the intensification of the westward auroral electrojet. Otherwise, the magnetospheric conditions are fairly quiet, with persistent northward IMF during the daytime hours of March 23. The contrast in the magnetospheric conditions between March 22 and 23 is of particular significance in distinguishing between the characteristics of events on these two days to be described in the following sections.

3. MERIDIONAL WIND DISTURBANCES

During the period of occurrence of the storm of March 22, 1979, the Saint-Santin radar was pre-programmed to monitor the winds and electrodynamical parameters primarily of the ionospheric *E* region. For this purpose, measurements were made at eight altitudes between 95 and 150 km in the *E* region and only at two altitudes in the *F* region in the daytime. During night when the electron densities in the *E* region were below the detection threshold, measurements were made at five altitudes in the *F*-region. In the *E* region where the drift due to ambipolar diffusion is negligible, the meridional wind velocity could be derived directly from the parallel component of the ion drift measured by the radar. (The directions « parallel » and « perpendicular » are with reference to the earth's magnetic (**B**) field.) On the other hand, in the *F* region where the ambipolar diffusion is significant, it was necessary to correct for the diffusion effect from detailed profiles of the electron density and electron and ion temperatures before it was possible to deduce the meridional neutral wind velocities (Amayenc and Vasseur, 1972; and Amayenc, 1975). Because of the preplanned observational schedule just described, such detailed profiles of density and temperature were available only at night during the storm period.

Figure 2 shows the *F* region meridional winds at night and the *E* region winds during the sunlit hours on March 22, 1979 as well as on the preceding and succeeding days. The wind variation on March 20, 1979 which is provisionally used as a control day, has also been superposed in this figure. The following features are evident from this figure.

1. The *F* region winds during the night previous to the storm onset are similar to the winds at night on the control day. On both nights, the wind switches direction from poleward (northward) to equatorward (southward) in the evening hours (2000 h LT) and remains equatorward for the rest of the night. The maximum equatorward wind speeds, attained not far from midnight, are of the order of 100 m/s. This type of wind variation is characteristic of the quiet-time sun-driven thermospheric circulation at night for these altitudes (Hernandez and Roble, 1984).

2. The *E* region winds on the day of the storm are comparable in strength to the winds on the control day, especially at the two higher altitudes shown. Mainly, the winds are under the influence of the semi-diurnal tide with an amplitude of about 25 m/s and a random superposition of short-period waves. However, there is also some indication of a mean poleward flow, of the order of 50 m/s, at the highest *E* region altitude of our observation. This net poleward flow is part of the daytime sun-driven thermospheric circulation, with a probable non-negligible contribution from the diurnal tide. At the lowest observation altitude of 120 km, however, this flow is presumably equatorward. The important point to be noticed here is that no wind disturbances are observed at Saint-Santin that are time-correlated with the forenoon (1054 UT) and afternoon (1436 UT) substorm events on this day.

3. However, a delayed response with dramatic changes in the thermospheric circulation is indeed observed at *F* region heights on the night after the substorms. Storm-induced equatorward motions make their first appearance at 350 km, probably no later than 0400 UT. They intensify during the rest of the early morning hours and have reached speeds in excess of 250 m/s when our observations are stopped according to our pre-programmed schedule.

4. Our *E* region data show equally strong evidence of wind disturbances on the day after the storm. These disturbances must have first reached these altitudes at night (when there are no observations). However, they are observed to peak about an hour after dawn

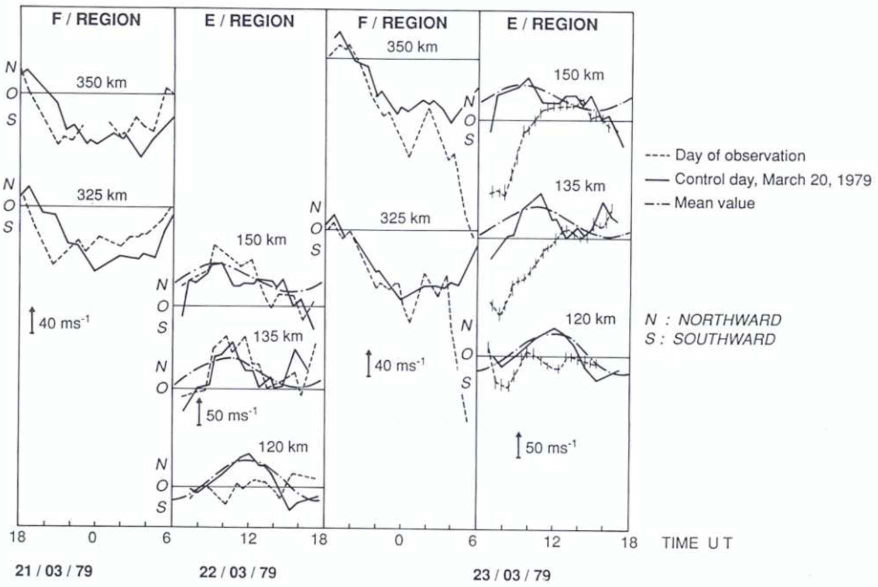

Figure 2

The F and E region winds measured by the Saint-Santin radar on March 21, March 22 and March 23, 1979. Winds in the E region were somewhat disturbed on March 20, 1979 which was initially used as a control day. We have therefore included an independent quiet-time model of wind variations obtained as the mean from March 20 to March 28, 1979.

with equatorward speeds of the order of 150 m/s at 150 km. The equatorward flow persists with diminishing strength at least down to 120 km and is found to last until local noon.

4. MIDDLE LATITUDE **E × B** DRIFTS

a) East-west drifts

Figure 3 shows the east-west and north-south components of the *F* region **E × B** plasma drifts measured by the radar on March 22 and March 23, 1979. This figure clearly illustrates the basic differences in character of the observed drift disturbances on these two days when the state of the magnetosphere was so obviously different. On the storm day of March 22, the rapid and rather large-amplitude oscillation in the east-west drift (amounting to a change of 10 mV/m in the electric field strength within a matter of 2 h) is apparently related to changes in direction of the IMF (Fig. 1) and consequent changes in the extent of penetration into the ionosphere of the convection electric field from the magnetosphere. These convection electric field disturbances have been successfully modelled by Senior and Blanc (1987). Otherwise, the disturbance drifts on this day are slightly westward in the morning and eastward in the late afternoon hours.

On the day after the storm there is a mean westward drift disturbance of magnitude of about 25-50 m/s and

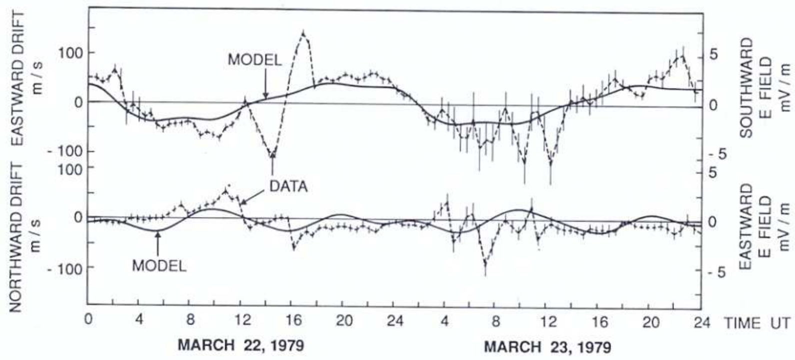

Figure 3

The eastward and northward **E × B** *drifts in* m/s *in the F region measured by the Saint-Santin radar on March 22 and March 23, 1979. The full line corresponds to the quiet-time model drifts according to Blanc and Amayenc (1979). The dashed line with error bars for individual measurements corresponds to the storm data. From the drift measurements the E field is deduced from the known value of B for the station and expressed in* mV/m *on the right hand side. Please note that the directions east and north are in relation to geomagnetic co-ordinates.*

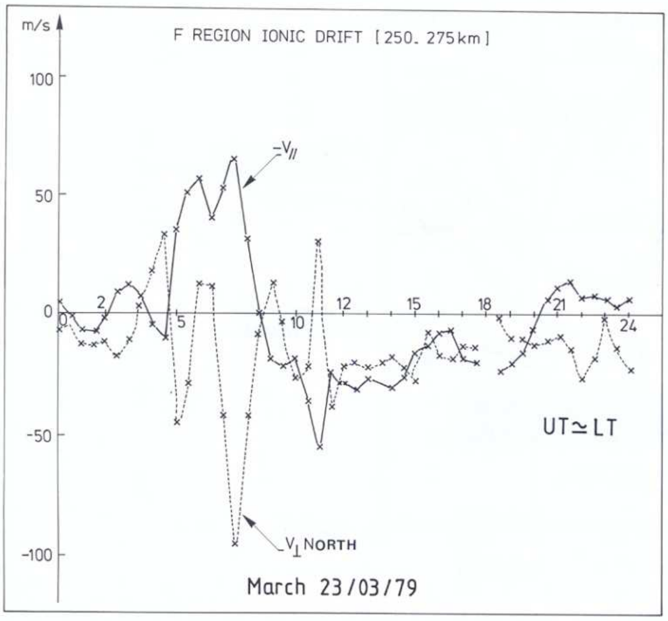

Figure 4
$V_{\perp N}$ (dashed line) and $-V_\parallel$ (solid line) measured by Saint-Santin radar on March 23, 1979. These drift components are in the magnetic meridian plane. Notice the anticorrelation in the oscillation of $V_\parallel$ and $V_{\perp N}$.

occurring at about the same time in the forenoon hours as the *E* region wind disturbances (Fig. 2). Superimposed on this mean drift disturbance, however, are strong oscillations of amplitude 100 m/s and of period 2 to 3 h. Moreover, these oscillations occur at the same time as similar oscillations in the northward drift, with which they seem to be sometimes correlated and sometimes anti-correlated. Prompted by the comments of one of the referees of this paper, we have resolved our drift data into anti-parallel ($-V_\parallel$) and perpendicular ($V_{\perp N}$) components in the vertical plane containing the magnetic meridian. We find that the oscillations in the $V_\parallel$ and $V_{\perp N}$ components are strongly anti-correlated (Fig. 4).

***b*) North-south drifts**

On the storm day of March 22, the north-south disturbances observed in Figure 3 are hardly as spectacular as the east-west disturbances. However, the north-south disturbances are found to respond to changes in direction of the IMF. Thus a directional shift in this drift component occurs at 1600 UT when the IMF shifts northward.

More attention should be focused, however, on the disturbances in this drift component on March 23. Apart from the pronounced fluctuations in this component noticed earlier, there is a mean drift disturbance in the forenoon and early afternoon hours, directed southward and of amplitude 35-50 m/s. This southward drift disturbance implies a westward or dusk-to-dawn electric field.

5. MIDDLE LATITUDE IONOSPHERIC CURRENTS

Figure 5 shows the height-integrated ionospheric current components deduced from our radar measurements according to the method adopted earlier by Mazaudier (1982). It should be mentioned in this context that the quiet-time currents at Saint-Santin reveal some apparently anomalous features: the currents are systematically northward and westward during most of the daytime hours with current strengths of the order of 20 amps/km (Mazaudier and Venkateswaran, 1985). Keeping this fact in mind, which is not well explained, we can still conclude that the observed ionospheric currents are intensified on the storm day, with a pulse of eastward and southward intensification centered around 1400 UT. This intensification occurs at the midpoint of a time interval when the IMF field direction is consistently southward (Fig. 1) and is probably in response to the inward penetration of the magnetospheric convection electric field.

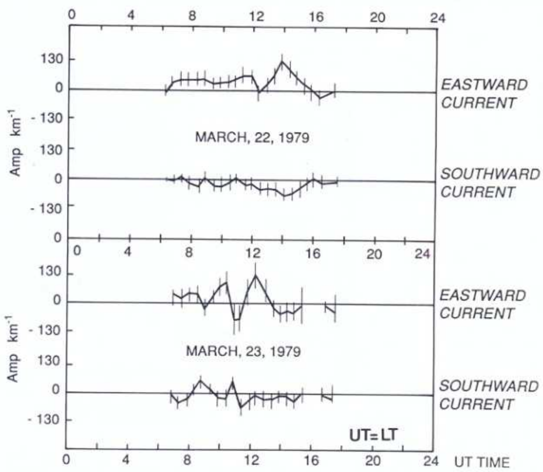

Figure 5
Height-integrated ionospheric currents over Saint-Santin on March 22 and March 23, 1979. Notice that there are strong eastward currents on both days.

The eastward currents are even stronger on the day after the storm when there is no conspicuous magnetospheric activity. There are large fluctuations in these currents consistent with (and consequent to) the electric field fluctuations although they appear much smoothed out in comparison to the latter (Fig. 3). As in the case of the electric field disturbance, the disturbance currents are sustained until about 1400 h UT.

The southward currents are not, in general, different between the storm day and the day after.

6. EQUATORIAL MAGNETIC DISTURBANCES

Figure 6 shows the equatorial magnetograms at Trivandrum, Addis-Ababa and Huancayo on the day (March 21) previous to the storm (full line) as well as on the day (March 23) following the storm (dashed line). The ionospheric disturbance (hatched area) on the latter day is identified and estimated by assuming that, apart from a constant difference of 36 nT which is to be attributed to changes in ring current intensities between March 21 and March 23 (Fig. 7), the quiet day magnetic field variations on these two days would have been identical. In this manner we deduce that :

1. Magnetic disturbances of ionospheric origin are observed at all the three equatorial observatories on the day after the storm (March 23). The magnitudes of the disturbances (~ 40 nT) are greater than the day-to-day variabilities for these stations on quiet days. Since the disturbances are observed in three observatories well separated in longitude, they are probably global in extent.

2. The disturbances occur almost exactly at the same local times (0900 to 1500 h LT) at these stations which are apart by almost 10 h in UT.

3. The disturbances are indicative of westward currents and electric fields at equatorial latitudes. These fields and currents are approximately 1/3 to 1/2 in magnitude and opposite in direction to their quiet-time values.

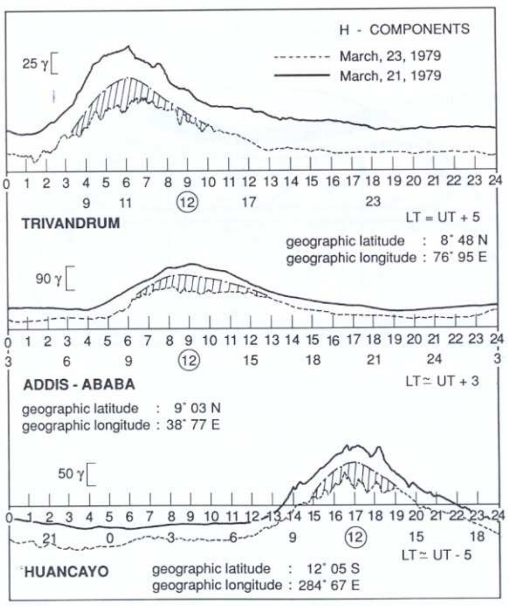

Figure 6

Trivandrum, Addis Ababa and Huancayo magnetograms (for March 21 (full line) and March 23 (dashed line), 1979. The dot-dashed line is obtained by subtracting the difference in Dst of 36 nT (Fig. 7) between these two days. The hatched area is identified as the disturbance of ionospheric origin. (Note that Addis Ababa is not included in the calculation of Dst published in Solar Geophysical Data.)

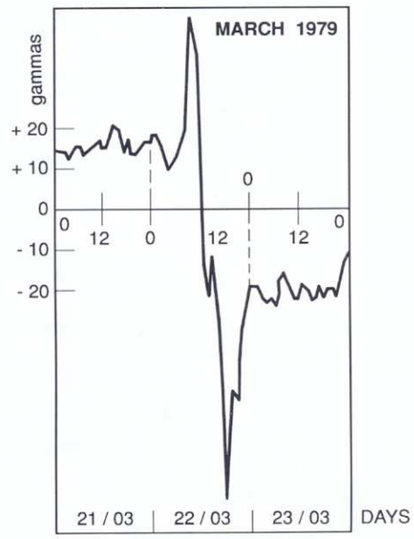

Figure 7

Dst indices for March 21, 22 and 23, 1979. Notice the steady Dst values on March 21 and March 23 amounting to + 15 nT and − 21 nT, respectively.

The equatorial magnetic disturbances on the day (March 23) after the storm are similar in character to what has been described by Mayaud (1982) and Fejer *et al.* (1983) and markedly different from the equatorial disturbances observed on the storm day (March 22) itself. Storm-time equatorial disturbances are known to occur at the same Universal Time in different stations (Nishida, 1968 ; Nopper and Carovillano, 1978 ; Fejer *et al.*, 1979 ; Kelley *et al.*, 1979 ; Gonzales *et al.*, 1983). Moreover, they are quite often related to either the storm sudden commencement (SSC) or directional changes in the B_z component of the IMF. For example, we see an increase in the H component associated with the SSC at 0826 UT at all three stations in Figure 8, this increase being more clearly evident in the Huancayo magnetogram. Similarly we observe reversals of the H component at 1230 UT and 1600 UT following the northward shifts in the B_z component (Fig. 1).

7. BLANC-RICHMOND THEORY (BR) OF THE DISTURBANCE DYNAMO

The disturbances in winds, electric fields and currents observed over Saint-Santin on March 23, 1979 as well as the equatorial magnetic disturbances, are presum-

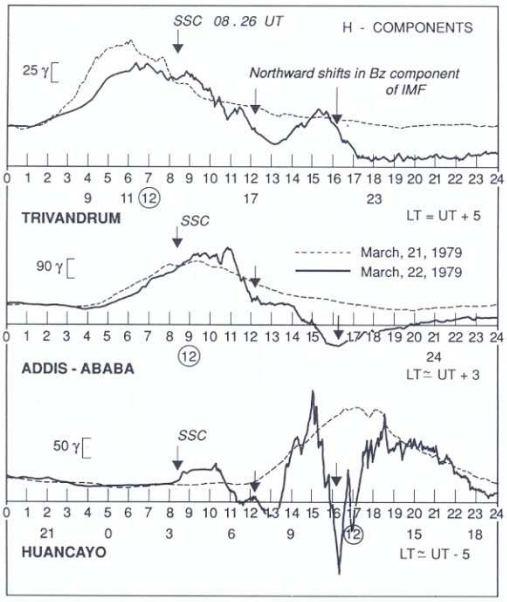

Figure 8

The equatorial magnetic disturbances on the storm day of March 22, 1979. *Notice the shifts in the H-component near the same universal times* (UT) *in all the three stations associated with the sudden commencement* (SSC) *and the northward shifts in the B_z component of* IMF.

ably of thermospheric and ionospheric origin because the state of the magnetosphere on this day is found to be fairly quiet (Fig. 1). Moreover, these disturbances appear to be global in extent. This suggests that the correlation of these disturbances may be sought in terms of the disturbance dynamo theory of Blanc and Richmond (1980) which is specifically concerned with disturbances of this nature. According to this theory, the observed disturbances are linked to the response of the global thermospheric circulation to storm-time heating at high latitudes. The heating results from the Joule dissipation of intensified sub-auroral currents and particle precipitation ; and the response consists of the generation of a meridional circulation extending from the latitude of the heat source to the equator and with equatorward winds at F region altitudes. The Coriolis force acting on the equatorward flow generates westward zonal winds (easterlies). These westward winds drive equatorward Pedersen currents in the ionosphere at altitudes near 150 km where the ionospheric Pedersen conductivity is high. Such Pedersen currents will tend to accumulate positive electric charges at the equator. The equatorial build-up of charge establishes a poleward electric field which opposes and eventually stops the Pedersen current flow. In turn, this poleward electric field which is perpendicular to the vertical component of the earth's magnetic field (downward in the Northern Hemisphere) drives eastward Hall currents (and westward plasma drifts). These eastward currents (and westward drifts) are expected to reach maximum intensity in middle latitudes. The currents are interrupted at the dawn and dusk terminators where the ionospheric conductivities have large longitudinal gradients. The interrupted currents set up polarization charges at the terminators and give rise to an electric field directed from dusk-to-dawn. Furthermore, the currents are deflected to higher and lower latitudes where they achieve closure through two separate vortices, a polar vortex and an equatorial vortex. These vortices have westward currents associated with them in the polar and equatorial regions, respectively. It is of importance to note that the equatorial disturbance current vortex has an opposite sense of flow to that of the quiet-time Sq current system.

The reader may wish to consult Figure 9 in following the somewhat cursory description of the BR theory contained in the previous paragraph.

8. COMPARISON OF THE DISTURBANCES OF MARCH 23, 1979 WITH THE PREDICTIONS OF BR

a) Qualitative comparisons

The directly verifiable points of comparison of the observed March 23 disturbances with the elements of BR are the following :

1) The appearance of wind disturbances spreading equatorwards from the region of heating at high latitudes as well as downward from F region to E region heights.

2) The establishment of poleward electric fields (westward $\mathbf{E} \times \mathbf{B}$ plasma drifts) and eastward ionospheric currents in the daytime ionosphere at middle latitudes.

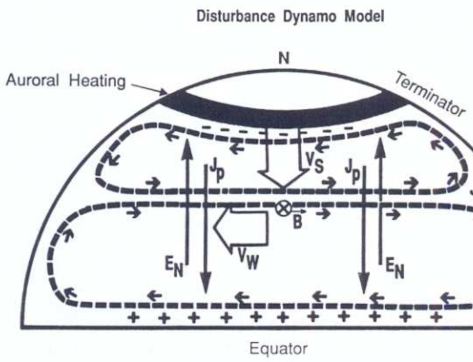

Figure 9

Schematic of the variables in the Blanc-Richmond (1980) *theory. The Joule heating from the storm is assumed to extend uniformly around a high-latitude zone. The southward meridional winds at F region heights arising from this heating is shown as the arrow V_s. Due to the action of the Coriolis force, the southward meridional wind produces westward zonal motion (shown as the arrow V_w). The zonal motion of the ions in combination with the downward component of the magnetic field (shown as $\otimes$ **B**) produces an equatorward Pedersen current (shown as J_p). The Pedersen current builds up positive charges at the equator until an electric field is established in the poleward direction opposing the flow of the Pedersen current. This poleward electric field is shown as E_N. This electric field which is perpendicular to the downward component of* **B** *gives rise to an eastward Hall current with maximum intensity in middle latitudes. This Hall current is marked as J_H. The Hall current is interrupted at the terminators and gives rise to two current vortices as shown. The lower latitude disturbance current vortex is opposite in direction to the normal Sq current vortex.*

3) The decrease in the H-component of the magnetic field at the geomagnetic equator resulting from overhead disturbance currents directed westward.

As noticed in Section 3, the arrival of the wind disturbance at Saint-Santin from higher latitudes is signalled by the sudden increase of the southward wind component in the F region, beginning from 0200 LT on March 23. This wind disturbance is already apparent in the E region by 0700 LT when observations at these heights begin. The E region wind disturbances are found to persist until noon. These observations of equatorward wind disturbances at our middle latitude station, appearing first at F region heights and then descending to lower altitudes, are in accord with the first of the theoretical elements of BR listed above.

As discussed in Section 4, there is a mean northward electric field disturbance (1.5-2 mV/m) in our data between 0006 LT and 1400 LT of March 23. The magnitude of this mean electric field disturbance is not large but it is still above our error of measurement and its direction which is poleward is in agreement with prediction 2) of the theory.

However, as earlier remarked in Section 4, overriding the mean disturbance are large amplitude (2-3 mV/m) oscillations which are present in both the southward and eastward electric field components, or even more clearly, in the parallel ($V_\parallel$) and perpendicular ($V_\perp$) components of the **E × B** ion drift. Notice that these oscillations are observed mainly before noon.

As mentioned in Section 4, one of the referees of this paper has made the suggestion that the oscillations may be similar to those reported from Arecibo (Walker, 1980 ; Bhenke *et al.,* 1985). The Arecibo measurements of the nocturnal F layer showed strong anticorrelation between $V_\parallel$ and $V_{\perp N}$ (north). As noted by Walker (1980), the most promising mechanism for explaining the anticorrelation in the short-period oscillations of these drift components might involve the diffusion mechanism. According to this mechanism, an upward $V_{\perp N}$ causes the F layer to rise. As the F layer rises, the downward field-aligned diffusion velocity increases. This increase in the diffusion velocity is seen as an increase in $V_\parallel$. Consequently, there is an anticorrelation between $V_\parallel$ and $V_{\perp N}$. Walker considered this situation to obtain in the nocturnal F layer. However, similar conditions can be simulated by storm-associated eastward electric fields and equatorward winds. In fact, Lunn (1989) has found from an examination of more recent Arecibo data that storm-related disturbances may have a tendency to excite or enhance the type of oscillations considered here even during daytime hours.

As noted in Section 5, the height-integrated disturbance ionospheric current is in the mean eastward when the mean electric field disturbance is northward. The disturbance currents, flowing mainly in the E region, respond to the electric field variations, common to both the E and F regions.

As discussed in Section 6, a decrease in the H component of the magnetic field was observed in different longitude sectors at the geomagnetic equator for the same period in local time (0700-1400 LT) on March 23, 1979. Such an equatorial magnetic disturbance fixed in Local Time rather than Universal Time is in accordance with BR. Moreover, the global geomagnetic analysis of Fambitakoye *et al.* (1990) for March 23, 1979 reveals that the equatorial disturbances at the three stations studied by us were part of a daytime disturbance current circuit with a clockwise circulation and running counter to the Sq current system, as predicted by BR.

As far as the timing of the equatorial magnetic disturbances are concerned, there is a 4 h time delay in UT between the onset times of the wind disturbances at Saint-Santin and the magnetic disturbances at Addis Ababa whereas for Huancayo the corresponding time delay is 15 h. According to BR, these time delays are related to the set-up time of the thermospheric circulation in response to high latitude heating ; they are best obtained by numerical modelling for conditions appropriate to the particular storm under study.

b) Numerical Model Simulations

Mazaudier *et al.* (1987) have attempted simulations of individual storms using a two-dimensional numerical model. They prescribed the high latitude Joule heating as independent of longitude and centered at 21° co-latitude. The intensity of the heating was parameterized as an empirical function of the AE-index (see Mazaudier *et al.* (1987) for details). The simulations were fairly successful for sufficiently long-lasting storms of moderate intensity. However, the simulation of the March 23 events failed to reproduce both the timing and magnitudes of the observed disturbances. It was clear from this simulation that the timing and intensity of the high-latitude heating for this specific set of events could not be parameterized in terms of the auroral index as it was for the other storms. The assumption of the longitude-independence of the heating could also have been seriously in error.

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