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Strange Currents Over Saint-Santin

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Analysis of 29 days of ionospheric current data obtained by Saint-Santin radar, including both magnetically quiet and disturbed periods, has confirmed the existence of northward currents at all daytime hours. The postulate of field-aligned Van Sabben currents driven by interhemispherical asymmetries seems to be able to account for the anomaly. The desirability of quantitative modeling of the Van Sabben currents on a seasonal or day-to-day basis is highlighted by the Saint-Santin measurements.

1. INTRODUCTION

In two previous papers, Mazaudier [1982] and Mazaudier and Blanc [1982] have reported and discussed the earliest measurements of ionospheric currents by the Saint-Santin incoherent scatter sounder. Surprisingly, these authors found that the measured currents were northward during the most of the daylight hours, even though the location of the station in the northern hemisphere would indicate that the currents should be southward in the morning and turn northward in the afternoon. They recognized that this anomalous effect is probably peculiar to the European sector because it has not been observed in the American sector by the Millstone Hill radar [Salah and Evans, 1977] and attributed its cause to field-aligned currents resulting from interhemispherical asymmetries in the manner first suggested by Van Sabben [1964, 1966]. In the present study we scrutinize the nature of the current anomaly with a larger body of data (29 days versus 3 days in the aforementioned studies) and, further, distinguish between geomagnetically quiet versus disturbed days.

2. METHOD OF CURRENT MEASUREMENT

Blanc et al. [1977] and Mazaudier [1982] have earlier described the methodology of ionospheric electric field and current measurements by the Saint-Santin incoherent scatter sounder. Basically, the radar measures the electron density \( N_e \) and the ion drift velocity \( V_i \) perpendicular to the geomagnetic field vector \( B \) at eight different altitudes in the E region (95, 100, 105, 110, 115, 120, 135, and 150 km) and two altitudes in the F region (250 and 275 km). It is assumed that (1) in the F region, \( V_{i\parallel} = (E \times B)/B^2 \) where \( E(E_{\parallel}, E) \) is the electrostatic field, (2) the field lines are equipotential with \( E_{\parallel} = 0 \) and \( E_z \) the same in both regions E and F, and (3) the electron gas is collisionless with \( V_{i\perp} = (E \times B)/B^2 \) at all altitudes of measurement. With these assumptions the local value of the current is directly obtained from the defining relation \( J = eN_e(V_i - V_e) \). The height-integrated currents are then calculated as

\[
J_x = \int_{Z_1}^{Z_2} J_z \, dZ \quad J_y = \int_{Z_1}^{Z_2} J_z \, dZ
\]

where the subscripts \( x \) and \( y \) denote the geomagnetic north and east directions, respectively, and it is supposed that the current layer is bounded at the top and bottom at levels \( Z_1 \) (90 km) and \( Z_2 \) (160 km) where the current density and its vertical divergence both vanish, i.e., \( J(Z_1) = J(Z_2) = (\delta J/\delta Z)Z_2 = (\delta J/\delta Z)Z_1 = 0 \). On the further supposition that the current layer is thin, vertical currents are neglected in comparison with the horizontal currents, and we obtain \( J_x = (1/\sin I)J_x \) and \( J_z = J_z \), where \( J_x \) and \( J_z \) are the height-integrated horizontal currents directed toward geomagnetic north and east, respectively, and \( I \) is the inclination of the terrestrial magnetic field. In the overhead equivalent current approximation we have the relations \( J_x = \Delta H \) and \( J_z = H \), where the currents are in amperes per kilometer and \( \Delta H \) and \( H \) are the related deviations in the northward and eastward geomagnetic field components expressed in nanoteslas. These relations include the conventional empirical correction factor for earth induction currents [Chapman and Bartels, 1940].

The radar current measurements are confined to the daytime hours of high enough \( E \) region electron densities.

3. DATA

Height profiles of northward and eastward horizontal currents have been deduced for \( E \) region altitudes (90–160 km) for 29 days, with one profile in general for every half hour between 0600 and 1800 UT. The days are classified as having weak or average magnetic activity, depending upon whether the daily sum of the 3-hourly \( K_p \) index was between 0 and 16 or between 16 and 32. Twelve days had weak magnetic activity, and 17 days had average magnetic activity in our data sample, according to this criterion. On three of the 12 days, the 3-hourly index exceeded 3 during daytime hours (0600 UT–1800 UT, \( UT = LT \)), indicating strong magnetic disturbance. The current profiles for the quietest (December 13, 1978) and the most disturbed (March 22, 1979) day in our data set are reproduced in Figures 1 and 2, respectively. It may be noted that our data are mostly for the seasons of winter and spring.

4. NATURE OF THE CURRENT ANOMALY

The current profiles like those shown in Figures 1 and 2 are height integrated, and the resulting overhead current values are used for the scatter plots in Figures 3–6. These plots for the north-south and east-west current components are given separately for the two selected categories of weak and moder-
Fig. 1. Half-hourly height profiles of ionospheric current components measured by Saint-Santin radar on the quietest day of our data sample (December 13, 1978). The solid line corresponds to the northward current, and the dashed line to the eastward one.

ate to high magnetic activity. Inspection of Figures 1–6 calls for two immediate comments:

1. The internal structure of ionospheric dynamo currents, first systematically revealed by radar measurements, is quite complex (Figures 1 and 2). Even on the quietest day in our data sample the two current components have time-evolving structures which are often multipeaked and are in antiparallel directions in adjacent layers.

2. Two points are made here: (1) height variation of the currents and (2) day-to-day variation of overhead currents is
large irrespective of the degree of magnetic activity (Figures 3 and 4); these two features may originate from the height and time variability of thermospheric winds, which is not our present topic of concern.

On the other hand, Figures 3-6 also reveal the following features of more immediate interest:

1. In spite of the scatter in the data points there is a systematic bias toward northward overhead currents on magnetically quiet days (Figure 3). This bias is retained and even slightly enhanced during magnetically disturbed days (Figure 5).

2. There is a similar bias toward westward currents on quiet days (Figure 4). This bias is less evident on disturbed days (Figure 6). These impressions are confirmed in Figure 7, where the plots show persistent daytime northward currents on both quiet and disturbed days as well as daytime disturbance currents whose directions are eastward. To understand in what sense these observations are anomalous, it is useful to refer first to the quiet \( (S_q) \) and disturbed \( (S_d) \) equivalent current systems deduced from geomagnetic data analysis for the longitude sector of our station [Mayaud, 1965]. The results of such analysis for the equinoctial season are reproduced in Figure 8. The analysis has been performed by assuming that \( S_q \) and \( S_d \) can be determined as the mean for the five quietest and the five most disturbed days of each month, the intensity of the magnetic activity being gauged by the \( K_p \) index. Important points to be noticed from Figure 8 are as follows:

1. At Abinger (51°N), which is to the north of Saint-Santin (44°N) but still outside of the subauroral region, the deviation of the \( H \) component of the magnetic field associated with \( S_q \) is negative and is indicative of westward equivalent currents during the day. The deviation in this component is also negative for \( S_d \). However, the \( S_d \) amplitude is weaker than the \( S_q \) one. This corresponds to a very weak eastward equivalent current disturbance.

2. At Toledo (40°N), which is south of Saint-Santin, the \( S_q \) variation is meager. We are thus able to locate the focus of the \( S_q \) as being close to the latitude of this station (we are unable to explain the large nighttime equivalent currents found for this station).

3. The stations north of Abinger are included in Figure 8 for completeness. They show the increasing influence of the eastward and westward electrojets in the \( S_d \) variations at higher latitudes. The curves labeled \( S_q \) for these stations are educated extrapolations of lower-latitude configurations.

We are now able to see two distinct features of the current anomaly over Saint-Santin from the standpoint of the geomagnetic equivalent current analysis. The first one is that the measured quiet time currents are northward during most of the day, whereas in consideration of the normal northerly location of Saint-Santin with respect to the dip equator, the meridional current should be southward in the forenoon and northward in the afternoon hours. This raises the question of the closure of the observed ionospheric currents. The second anomalous feature is that the equivalent disturbance current shows a weak eastward intensification at a station to the north of Saint-Santin smaller than the eastward intensification of ionospheric disturbance currents over Saint-Santin. At this point we must recall that the dispersion of the ionospheric eastward electric current is very large (see Figure 6).

5. CONFIRMATION OF THE ANOMALY

It seems reasonable to ask whether the current anomaly described above is supported by the wind and electric field data, also obtained from radar measurements of the parallel and perpendicular components of the ion drift velocity. Such a consistency check has been performed by Mazaudier and Blanc [1982] for a sparser data set by evaluating the current densities from Ohm's law: \( J = \sigma(E + V \times B) \), where model winds and electric fields derived from the radar data were used in conjunction with independently derived values for the conductivity tensor. Details are to be found in the work of Mazaudier and Blanc [1982].

The results of a such a consistency check for our quiet time
current data are shown in Figures 9 and 10. It is evident that the existence of daytime northward currents is a persistent feature in the different seasons under quiet geomagnetic conditions and that our present data fall reasonably well between the expected values for winter and spring (Figure 9). Thus this feature of the quiet time current anomaly is apparently real.

The electric current model based on electric field and neutral wind data is local, and the electric fields are not derived from the neutral winds. To understand the electric current anomaly, it would be necessary to calculate the global electric field and current distribution resulting from a global model of neutral winds by using a dynamo model.
Figure 10 reveals, however, that the consistency check is not equally successful for the eastward current component. Our data show westward currents, as would be appropriate for a station fairly to the north of the \( S_q \) focus. But the test values derived from average wind and electric field models for the different seasons seem to indicate weaker currents and, accordingly, a closer location of the station with respect to the focus. This discrepancy can arise, for example, from the sensitivity of the focus location to geomagnetic activity [Hasegawa, 1960]. The average wind and electric field models used to define the electric current variation shown in Figures 9 and 10 were, in fact, derived for periods of somewhat lower geomagnetic activity than was common to our present series of measurements.

When we discuss the observed anomaly related to disturbance currents, it is important to consider the influence of the...
equatorial ring current. The ring current contributions to the ground magnetic variations at 45°, which is close to the latitude of Saint-Santin, are displayed separately for the quiet and disturbed days of our data sample in Table 1. It is found that this contribution amounts to a southward field component of 15–20 nT during disturbed days. This gives rise to a westward component of the equivalent current of the order of 15–20 A/km. This is comparable to the eastward ionospheric disturbance currents measured by radar (Figure 7) and can effectively mask a part of the influence of the latter in ground magnetic data. Thus the fact that the \( S_d \) variation is very similar to the \( S_q \) one is explicable as the ring current effect.

We must still explain why the ionospheric disturbance currents (disturbed day currents minus quiet day currents) are eastward. Figure 11 shows the average F region \( E \times B \) ion drifts measured by radar for our quiet and disturbed day samples. It can be seen that the disturbance drifts (disturbed day drifts minus quiet day drifts) are generally westward and are intensified in the afternoon hours. Associated with this drift
component must be a northward electric field disturbance and an eastward Hall current disturbance. In addition, Figure 11 shows that there is comparatively little change in the north-south drifts from quiet to disturbed days and hence only a small extra disturbance time east-west electric field. These fields must drive Pedersen currents in the east-west direction depending on the time of day. Figure 12 shows that the net disturbance currents due to the combination of Hall and Pedersen currents is eastward as observed. However, the strength of the observed currents is greater in the forenoon and weaker in the afternoon hours when compared to the currents calculated as arising from observed electric field disturbances alone. This fact could be explained by the inclusion of the induction (dynamo) electric field resulting from disturbance winds [Blanc and Richmond, 1980]. These winds directed equatorward can give rise to additional eastward currents and offset to some extent the morning discrepancy between observations and calculations. But this phenomenon will add to the discrepancy in the afternoon hours. Thus our consistency check reveals a residual of westward disturbance currents in our observations. Since this residual is in apparent violation of Ohm's law, it can only arise as an error resulting from the unrealistic upper boundary condition that has been imposed on the data reduction procedure, namely, that there are no sources and sinks due to parallel currents at higher levels. (An alternative explanation that the wind was southward in the morning and northward in the evening hours, on the average, for the particular days of disturbance used in this study, appears more contrived.)

6. Resolution of the Anomaly

The preceding discussion has brought us back to the starting point: The strangeness of Saint-Santin currents lies in the northward meridional component. It is a reasonable assumption that this current component is peculiar to, or at least more pronounced in, the longitude sector of Saint-Santin. As stated earlier, no similar currents, either northward or southward, have been detected at the comparable latitude of Millstone Hill in the American sector. The closure of these meridional currents should therefore be achieved through a current circuit in which the compensating southward currents also flow in the same longitude sector but at high enough altitudes that the parallel plasma conductivity is extremely large and the currents are likely to be field aligned.

These qualifications of the postulated current circuit are satisfied by Van Sabben [1964, 1966] currents whose probable role in the Saint-Santin anomaly has been earlier recognized by Mazaudier and Blanc [1982]. The origin and properties of the Van Sabben currents are related to several factors: (1) the obliquity of the geomagnetic dipole axis with respect to the earth's rotation axis, (2) the differences in the induction (dynamo) electric fields at the foot of a field line in the two hemispheres resulting from equatorially asymmetric wind systems, and (3) seasonal differences in ionospheric conductivities. These causes are responsible for the observed asymmetry between the $Sq$ current systems in the two hemispheres at any
given time. Van Sabben, in fact, started from the existence of this asymmetry to infer the nature of the currents, which in this paper we have chosen to name after him. The asymmetry is revealed both in the total currents carried by the two Sq systems and in the longitudinal differences of their focus positions. It is particularly strong in the European longitude sector of Saint-Santin in the solstitial seasons [Matsushita, 1967; Suzuki, 1978].

It would appear that the Van Sabben currents enter the ionosphere of the northern hemisphere in the evening hours and leave it in the forenoon hours during autumnal equinox, according to the analysis of Van Sabben [1966] based on one day.

If similar currents persist for seasons appropriate to this study, they can account for the observed meridional currents northward as well as for some westward current over Saint-Santin. From the observed strengthening of northward currents during storm periods we are led to infer a corresponding intensification of Van Sabben currents.

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**Table 1.** Influence of the Ring Current on the Mid-Latitude H Component, Deduced From the Dst Equatorial Index (AIf = Dst cos i, i = Latitude)

<table>
<thead>
<tr>
<th>Time, UT</th>
<th>Disturbed (17)</th>
<th>Quiet (12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0100-0300</td>
<td>-3</td>
<td>-5</td>
</tr>
<tr>
<td>0300-0500</td>
<td>-5</td>
<td>-5</td>
</tr>
<tr>
<td>0500-0700</td>
<td>-5</td>
<td>-5</td>
</tr>
<tr>
<td>0700-0900</td>
<td>-5</td>
<td>-5</td>
</tr>
<tr>
<td>0900-1100</td>
<td>-5</td>
<td>-5</td>
</tr>
<tr>
<td>1100-1300</td>
<td>-5</td>
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</tr>
<tr>
<td>1300-1500</td>
<td>-5</td>
<td>-5</td>
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<tr>
<td>1500-1700</td>
<td>-5</td>
<td>-5</td>
</tr>
<tr>
<td>1700-1900</td>
<td>-5</td>
<td>-5</td>
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<tr>
<td>1900-2100</td>
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<tr>
<td>2100-2300</td>
<td>-5</td>
<td>-5</td>
</tr>
<tr>
<td>2300-0100</td>
<td>-5</td>
<td>-5</td>
</tr>
</tbody>
</table>

Units are $\gamma = 10^{-7}$ T.

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**Fig. 11.** Average observed eastward and southward $E \times B$ drifts on quiet and disturbed days in Table 1.

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**Fig. 12.** Average Hall and Pedersen eastward currents driven by the observed electric field disturbances (upper panel) compared with the currents deduced from measurements for the disturbed period (lower panel).
Our hypothesis of field-aligned currents over Saint-Santin may be testable from geomagnetic $D$ component records. Examination of such records from Chambon-la-Forêt, which is the nearest observatory to our radar station, indicates northward currents in the afternoon hours; these currents show evidence of enhancement during disturbances (Figure 13). Thus these records essentially support the radar observations with no additional clues about field-aligned currents.

Alternatively, it should be possible to model the current system for individual days or on a seasonal basis. Stening [1970] and Richmond [1974] have outlined methods of calculating field-aligned currents which are readily programmable. Using Richmond's [1974] method, Schieldge et al. [1973] and Schieldge [1974] have modeled the three-dimensional $S_q$ system including field-aligned Van Sabben currents. These studies were able to show that the equatorial $D$ variations produced by field-aligned currents should be detectable by ground magnetometers. Since these early studies our ability to understand and model ionospheric disturbance currents has been advanced [Blanc and Richmond, 1980]. It should now be possible to simulate the observed Saint-Santin ionospheric currents for quiet as well as disturbed periods.

7. CONCLUSION

In this paper we have presented and discussed the ionospheric currents measured by Saint-Santin radar. The anomaly of systematic northward currents over most of the daytime hours, earlier found by Mazaudier and Blanc [1982], is confirmed from a larger body of data. The anomaly is shown to be a persistent feature of both quiet and disturbed days.

The existence of the anomaly is traced to field-aligned Van Sabben currents, not directly detected by the radar. The apparent longitudinal limitation of the anomaly is consistent with this hypothesis. The testing of this hypothesis calls for future modeling efforts.

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