The 'separation' procedure described in Part I has been used to divide the $Sq$ current system into three subsystems. The first of these is associated with seasonal variations and has current strength of about 100 kA. Its origin appears to be semi-diurnal winds.

The second subsystem is called the 'Fuquene' system and has a strength about 150 kA ($\pm 50\%$). It appears to be due to magnetospheric sources and, at least at the equator, may not flow at ionospheric heights.

The third subsystem is called the 'constant' and has a strength of about 220 kA ($\pm 50\%$). It is possibly due to direct ionospheric heating.

1. Introduction

The 'separation' method of analysis allows one to isolate a particular current system associated with a specific magnetic variation. It was explained and applied in Part I of this study to show two of the current systems associated with the equatorial electrojet. These current systems were the lunar current system and the 'random component' current system which are associated with the equatorial electrojet.

The 'separation' procedure uses as 'x' input, the magnetic variation for which one wishes to deduce the associated current system. Another variation which could be used as 'x' input is the seasonal variation of electrojet intensity which showed clearly in Fig. 5 of Part I. That figure was a plot of electrojet range versus time of year for 1964 and an obvious semi-annual variation of amplitude could be seen.

This same semi-annual variation is shown more clearly here in Fig. 1 which is a plot of the mean amplitudes in the months of 1964. DANIELS (1974) examined the seasonal variation for a large number of stations and showed that this semi-annual variation with maxima in equinoxes is very typical.

2. Analysis and Results

The seasonal variation shown in Fig. 1 was used as an 'x' input and a separation was performed by the method described in Part I. For 'y' input instead of daily values for each hour monthly average values for each hour were used.

The current system 'separated' out is shown in Fig. 2. A particularly clear pattern is obtained despite the fact that the input data was only the 12 monthly values.

The northern hemisphere system is a counterclockwise loop centred on (32°N,
1000 hr). The southern hemisphere system also appears to be dominated by a single loop centred on (about 20°S, 1130 hr). Taking (from Fig. 1) that 45 nT, the approximate peak-to-peak amplitude of this seasonal variation, corresponds to \( c = 1 \) the calculated total current in the northern loop is about 69 kA and in the southern, 143 kA.

3. Discussion of the Seasonal Variation Current System

The question which arises immediately is whether the variation and the associated current system is just an intensification of the standard \( Sq \) current system. Certainly the current system of Fig. 2 closely resembles the \( Sq \) system. The only obvious difference is a slight difference in positions of the foci. Examination of the magnetic records for 1964 shows that the northern focus of the \( Sq \) system was between San Juan and Dallas. This is a higher latitude than the focus in Fig. 2.

Further evidence that the foci positions for the two systems are different is
furnished by Daniels (1974) who found that while all the other stations showed horizontal range increase in equinox, the two stations San Juan and more notably Honolulu just south of the $S_q$ focus showed range decreases in equinox. This would happen if the seasonal variation current system had a focus south of these stations whereas the $S_q$ focus is north of these stations. There is, therefore, some slight evidence that the system shown in Fig. 2 is not just the $S_q$ system. This question will be further discussed after the cause of the seasonal variation is investigated.

Probably the annual variation of electrojet intensity shown in Fig. 1 is not due to any one cause but is the sum of several effects. Seasonal conductivity changes must play some part in the variation. Daniels (1974) showed that while the seasonal variation of Fig. 1 is typical on virtually a global scale, individual stations also showed a variation which could be more directly related to conductivity. He concluded that the Fig. 1 variation was not related to conductivity in any simple way. It is therefore assumed that the principal cause of this variation is not conductivity changes.

The hypothesis which will next be investigated is that the seasonal variation of Fig. 1 and the current system of Fig. 2 is predominantly due to the seasonal variation of a single wind component. Data on the seasonal variation of semidiurnal, diurnal, and steady wind components in the dynamo region were examined to see whether any had a seasonal variation similar to Fig. 1.

There are so many papers on winds that it is possible, of course, to find some results which show variations similar to that of Fig. 1. A comprehensive survey, however, did not find any strong evidence that the steady, diurnal, or semidiurnal winds in the dynamo region had the required variations. In fact the survey mainly revealed that knowledge about these components in the dynamo region is still very uncertain. Theoretical work on the dynamo effects of steady and diurnal winds (see Richmond et al., 1976; Stening, 1969) shows that the steady, and the propagating diurnal mode winds, are not very efficient at producing current systems. Non-propagating (negative) mode diurnal winds are shown to be efficient producers of dynamo currents. There is no evidence that these non-propagating mode winds which are directly excited in the ionosphere should have a pronounced seasonal variation. Attention therefore was focused on the semidiurnal wind systems which are also reasonably efficient in driving dynamo currents.

To attempt to obtain more information about the seasonal variation of the semidiurnal component in the dynamo region an earlier study of winds using sporadic E data (MacDougall, 1974) was extended. The results of this study (MacDougall, 1978) showed that the semidiurnal component is indeed quite prominent and further that the seasonal variation is also prominent, being a strong maximum in local summer. This seems to be the opposite of Fig. 1 (since the current systems here include both hemispheres a summer maximum would probably show at the electrojet in both June and December). It is, however, possible to interpret Fig. 1 as a decrease in solstices rather than as an increase in equinox. If this interpretation is valid it merely means that the currents of Fig. 2 should be...
reversed. To verify Fig. 1 as a decrease at solstices due to the observed semidiurnal winds it is necessary to show that the observed semidiurnal winds do give a current system which is the reverse of Fig. 2.

The study referred to above showed that the best fit to the observed sporadic E data would be a combination of 2,2; 2,3; and 2,4 mode winds. This, of course, makes it impossible to use any standard published dynamo calculation which uses a single mode wind system. A further problem is that if the Fig. 1 variation is the sum of a decrease in June solstice due to the strong northern hemisphere semidiurnal system, and a decrease in December solstice due to the strong southern hemisphere system, then these two systems are superimposed in Fig. 2. This makes theoretical verification more difficult. To attempt to unscramble this figure the year was divided into two halves; April through September (referred to as the June solstice period), and October through March (referred to as the December solstice period). The seasonal variations were separately calculated for these two periods using the same process as for Fig. 2 and are shown in Figs. 3 and 4. In spite of each of these figures being derived from only 6 sets of values the current systems are surprisingly clear. They both show more structure than does Fig. 2 (some of the structure has obviously cancelled out in Fig. 2 which is approximately the vector sum of these two figures). An interesting feature of both Figs. 3 and 4 is the strong N-S current flow just after sunrise directed from winter to summer hemisphere (or in the reverse direction if the seasonal variation is a decrease at solstices). If one of these figures is inverted and aligned on the other along the equator it may be seen that the main features coincide well. This is in agreement with the earlier hypothesis. It remains therefore to see whether the winds deduced from the sporadic E data will cause a current system like Figs. 3 or 4 (with the reverse of the current vector shown).

![Fig. 3. Normalized current system associated with the seasonal variation for the June solstice.](image-url)
The most obvious feature of these current systems which indicates a semi-diurnal component is the pairs of counter-rotating current with spacings of the order of six hours. These show up clearly on Figs. 3 and 4 (less obviously on Fig. 2 where a certain amount of cancellation has taken place). Figure 4 resembles Fig. 7 of Part I which showed the lunar current system for January. The lunar system is, of course, almost pure semi-diurnal. The type of current patterns therefore which are seen here for the seasonal variation are typical of those for semi-diurnal wind systems. It remains next to show that the flow of current is reversed in Fig. 2, 3 and 4 for the semi-diurnal system which represents the sporadic E data. The problem here is that none of the standard dynamo calculations (e.g. RICHMOND et al., 1976; STENING, 1968; 1969; TARPLEY, 1970) have the same combination of tidal modes or height variation of these modes which appear to be valid for the sporadic E data. To avoid therefore some of these problems the data for the lunar system is used here. It is presently accepted that the lunar wind system should compare more directly with the 2,2 mode than with other wind components such as the 2,3 and 2,4 which are also necessary in order to fit the sporadic E data. Therefore, this comparison should not give detailed agreement, just the direction of the currents.

For the lunar wind system, a comprehensive survey is given by MATSUSHITA (1967a) and from his data the maximum eastward lunar winds at 110 km would be at about 0600 hr lunar time. This time is estimated from the data presented by Matsushita on the lunar winds which are quite imprecise and also his data on lunar variations of sporadic E heights (which should be at a maximum at the time of maximum eastward winds) which show better consistency. Since the lunar current system usually maximizes about 2 days after new moon (see Part I) this means the maximum lunar eastward wind would be at about 0800 hr solar time. This lunar

[Diagram of normalized current system associated with the seasonal variation for the December solstice.]
phase is such that E-W reversals would be at 1100 and 2300 hr and this is almost exactly in opposite phase to the 2,2 mode semidiurnal winds which fit the sporadic E data. Therefore, by comparison with the lunar winds and currents the directions in Figs. 3 and 4 (and therefore 2) should be reversed. This is in agreement with the hypothesis that the seasonal variations are a decrease at solstices rather than an increase at equinox.

If the above hypotheses are correct it means that the seasonal variation current system as shown in Figs. 2, 3, and 4 is not at all the same as the average $S_q$ system. In fact up to this point none of the current systems which have been separated out (these are the lunar, random and seasonal) appears to have a common origin with the average $S_q$ system. It is necessary now to look again at the data to see if there are other current systems also superimposed on the $S_q$ system.

4. The 'Fuquene Current Systems'

Up to this point the primary variation which was used in the 'separation' analysis was taken from the equatorial electrojet. The analysis based on these has only answered half the original question which was 'why do the electrojet variations not correlate with the $S_q$ system variation?' The answer to half of this question is that the particular current systems are associated with the electrojet variations, and all of these are different from average $S_q$ system. The other half of the question will now be looked at by using the separation analysis to show the current systems associated with magnetic variations which affect only the 'S$Q$ system'. In the current plots given in Part I for electrojet associated current systems (Figs. 2, 3 and 4 of Part I) it will be noted that Fuquene at midday has no horizontal (E-W current)
component associated with the electrojet variations. Therefore, the midday Fuquene $H$ variation should possibly give information about current systems uncorrelated with the electrojet variations.

The separation procedure and the handling of the data was discussed in Part I.
and the same basic analytical process was used here. For ‘x’ input in the ‘separation’ average midday values of the Fuquene horizontal magnetic component were used. These were taken as the average of the hours 10, 11, 12. Results of the separation are shown in Figs. 5, 6, and 7.

As well as using the Fuquene average midday horizontal component for ‘x’ input, the Fuquene horizontal range calculated in the standard way was also tried as ‘x’ input. Results were almost identical, but since current patterns using just the average midday horizontal component did seem slightly clearer they are shown here.

For July, Fig. 3, a small correction: 1/6 of the electrojet range, was added to the average Fuquene midday horizontal values. For the reason for this correction it is necessary to go back to Figs. 2, 3, and 4 of Part I. These show that while in January and April there are no average midday east-west currents associated with the electrojet over Fuquene (and therefore the midday Fuquene and electrojet horizontal components would be uncorrelated), in July there are midday westward currents over Fuquene associated with the eastwards electrojet flow. To obtain the Fuquene component which is uncorrelated with the electrojet it is necessary to introduce a correction for these westward currents. It was found that adding 1/6 of the electrojet range to the Fuquene midday horizontal component produced the required zero correlation. For July, therefore, the Fuquene midday horizontal components have been ‘corrected’ before use as ‘x’ input.

5. Results of the Analysis of the Fuquene System

The current systems of Figs. 5, 6, and 7 are similar in many ways. The summer hemisphere part of each system is obviously dominant and in January, Fig. 5, the southern hemisphere system appears to penetrate as far north as a point between San Juan and Dallas while in June, Fig. 7, the northern system penetrated as far south as the data goes. The April system, Fig. 6, is approximately intermediate between the other two systems with a tendency for the northern system to dominate. The Fort Churchill data clearly show that these systems are strongly connected with the auroral zone. Note that the Fort Churchill current vectors have been scaled down by a factor of 2 and yet they are still strikingly large.

Current strengths for these systems are estimated using the standard deviations of the Fuquene horizontal variations to scale $c=1$. These are 13.7, 9.9 and 11.5 nT in January, April and July respectively. Using these scales the following total currents are obtained: January, current in the southern loop estimated from the north-south flow at Pilar, 56.5 kA; April, current in the northern loop estimated from the north-south flow at Dallas, 48.7 kA; July, current in the northern loop estimated from the north-south flow at San Juan, 40.2 kA. The average strength of these current systems is therefore about 48 kA. By comparison to systems shown in previous parts of this study, these are not notably strong.
6. Discussion of the Fuquene System

The immediate thing which was noted about these current plots, in particular Fig. 6, was the striking similarity to the electrostatic fields pattern shown by Matsushita (1972). Matsushita showed the required dynamo region electrostatic fields for the \( S_q \) to be driven by magnetospheric sources.

As well as the similarity to Matsushita's fields, the rather obvious connection with the very strong currents over Fort Churchill in the auroral zone also implies that these current systems may be driven by magnetospheric sources. If this identification is correct one wishes to know how large this current system is on an average day since the total current figures given above are those of the day-to-day variation of this component and do not show how strong this system is on an average day. In order to answer this question it is necessary to examine the equatorial portion of the current systems shown in Figs. 5, 6, and 7.

The current plots for the Fuquene system show currents over the dip equator which are approximately of the same value as over Fuquene. This is as expected since the method of separating the electrojet components was \( \Delta H \) (electrojet) = \( \Delta H \) (Fuquene) - \( \Delta H \) (Huancayo). Since the electrojet is uncorrelated with these "Fuquene" systems then approximately \( \Delta H \) (Fuquene) = \( \Delta H' \) (Huancayo) as observed. Therefore there is a current system at Huancayo which is not correlated with the electrojet.

It has been shown (MacDougall, 1969) that there is a very high correlation between the strength of the electrojet and the ionospheric equatorial anomaly in the \( F \) region. Since both these are driven by eastwards electric fields, the electrojet in the \( E \) region, and the anomaly at least partly in the \( F \) region, the very high correlation between these two phenomena implies that the same electric field extends throughout the ionospheric region at the dip equator. Therefore in order to have a current system at the equator which does not correlate with the electrojet it is necessary that either (a) the currents are driven directly by winds without an attendant electric field appearing, or (b), the currents do not flow in the ionosphere.

Evidence for the latter possibility is the absence of distinctive day-night changes in the current plots of Figs. 5, 6, and 7. The changes of \( E \) region conductivity at sunrise and sunset tend to be dramatic and show up clearly on some of the earlier current plots (see also Part I). Conductivity changes at sunrise and sunset are much less pronounced for higher ionospheric regions. The absence of notable day-night effects in Figs. 5, 6, and 7 therefore implies that current flow is in upper ionospheric levels or above.

There is some doubt that the extent of the nighttime current flow is fully revealed in these figures. As described in Part I, east-west current 'zero levels' were adjusted to give no average east-west currents at midnight which is a reasonable assumption if most of the conductivity is associated with the \( E \) region. If this adjustment had not been made for the present data there would have been additional eastwards-directed "ring-current"-like systems of normalized vector magnitude approximately
0.18, 0.25, and 0.35 in January, April and July respectively. Adjustments to north-south currents used a different assumption and were small and random.

Returning again to the question regarding the magnitude of these ‘Fuquene’ current systems on an average day; the evidence above—that these are not driven by electric fields in the lower equatorial ionospheric regions—will be used to attempt to estimate their magnitude. It is not valid to just take the magnitude of the Fuquene horizontal variation on an average day as an estimate of the strength of this system since it is very possible that part of this average daily variation could be due to a ‘constant’ lower ionospheric current system. The investigation here, which relies on variations to perform a ‘separation’, has revealed nothing about any ‘constant’ system. By ‘constant’ is meant that portion of the current system which does not change in form or intensity from day-to-day.

The method which will be used to attempt an estimation of the intensity of the average ‘Fuquene’ system is to assume that, as discussed above, the Fuquene system is ‘non-ionospheric’ but that all other systems including any constant systems are driven by electric fields in the ionosphere and therefore will show an equatorial electrojet enhancement. It is possible then, as shown below, to use the observed form of the electrojet enhancement to estimate the magnitude of the ‘ionospheric’ component and to subtract this to leave the ‘non-ionospheric’.

It is first necessary therefore to determine to what extent the electrojet would enhance the currents in that particular region if the eastwards electric field throughout the entire equatorial zone has the same value. A recent model calculation by Richmond (1976) gives the latitudinal current profile for the equatorial region shown in Fig. 8. Note the small width of the electrojet enhancement and also the magnitude of the enhancement. The width is in good agreement with other data on the width of the electrojet in the American zone (e.g. Rastogi, 1962; Knecht and McDuffie, 1962). There is no experimental data to verify the calculated magnitude of the enhancement. The upper limit for the calculation was taken by Richmond as 200 km. If the upper limit had been higher there would be an increase of the ‘base line’ current levels outside the electrojet. Using data from Matsushita (1967b) the estimated base line should be shifted upwards by about 15% to approximately 37 A/km. The current enhancement by the electrojet then is close to a factor of 7. The magnetic field enhancement which would be observed on the ground under the electrojet due to this electrojet enhancement is also shown on Fig. 8 (this is an approximation having the electrojet as a sheet current at 105 km and a flat earth). This enhancement is about a factor of 4.8.

Using the magnetic field enhancement curve of Fig. 8, it is seen that comparing a pair of stations such as Huancayo (dip latitude 0.65°) and Arequipa (dip latitude −2.9°) which are sufficiently close together that the large scale ionospheric electric fields should be the same at both, any difference in the fields would be due to the equatorial enhancement of the electrojet over Huancayo. An estimation of the magnetic field enhancement of Huancayo relative to Arequipa from Fig. 8 is about a factor of 2.
Unfortunately Arequipa is far from ideal in many respects. The Arequipa magnetic data were only available as mm of deflection and scales had to be estimated. Also, the close proximity of Arequipa to the coast leads to a suspicion that some anomalous results from Arequipa data might be due to 'coastal effects' (see PRICE, 1967). Furthermore, the location of Arequipa on the side of the enhancement curve (Fig. 8) makes the value of the enhancement greatly influenced by slight shifting of the electrojet, uncertainties in the model, etc.

For the above reasons, the calculations which will be presented below used La Quiaca as the comparison station (see Fig. 8). Being further from the dip equator however, the assumption that the electric field will be the same as at Huancayo is not quite so valid.

Using then the Huancayo and La Quiaca average ranges, $\Delta H$, the enhancement profile of Fig. 8 gives the result that $(\Delta H$ ionosphere plus electrojet) $\approx [(\Delta H$ Huancayo) $- (\Delta H$ La Quiaca)] $\times 1.375$. For April, $(\Delta H$ Huancayo) = 113.8 nT, $(\Delta H$ La Quiaca) = 50.1 nT giving $(\Delta H$ ionosphere plus electrojet) = 87.5, and therefore $(\Delta H$ Fuquene system at equator) = 26.2. Similar calculations in other months gave comparable values. Taking into account that Fig. 6 shows a decrease of the Fuquene system south of the dip equator which would result in an underestimation of the strength of this system using the above procedure, the value 30 nT $\pm 50\%$ was used as the estimate for the average range of the Fuquene system at the dip equator in April. As shown by Fig. 6, this range at the equator corresponds closely to $c=1$. Therefore, 30 nT is taken as a first estimate for $c=1$ scale in the April system.
Using this, the total current in the northern current loop of Fig. 6 is estimated from the north-south flow at Fuquene at 150 kA ±50%.

7. The ‘Constant’ Current System

In all previous parts of this study current systems were ‘separated’ by using their day-to-day variation. There is still another possible system. This is termed the ‘constant’ system since it is essentially constant in form and intensity throughout the entire year.

To examine this part of the \( S_q \) current system it is necessary to remove the other components whose properties have been determined in the preceding parts of this study. The ‘random’ component and the lunar component described in Part I are variations whose average is zero so are not of interest here.

The seasonal component described earlier can be eliminated by choosing a month when this component has a value close to zero. From the earlier discussion the best estimate would be to assume that the seasonal component is a minimum closely equal to zero in March equinox (i.e. April). Therefore, April data should be relatively free from the effects of the seasonal variation. Next it is assumed that the \( S_q \) current system for April is composed of just the Fuquene component described above and the ‘constant’ component. One can obtain an approximation of the \( S_q \) system which is assumed to be the sum of these two components by using the average values of the daily magnetic variations for individual stations on quiet days in April. Having done this, the ‘Fuquene’ component of Fig. 6 (with estimated magnitude corresponding to \( c=1 \) of 30 nT as discussed above) was subtracted to yield the ‘constant’ system which is shown in Fig. 9.

![Fig. 9. Current vectors of the ‘constant’ current system. This is the ionospheric system which is always the same strength and form.](image-url)
This current system is not greatly different from a ‘standard’ $S_q$ system. There appears to be a focus at about (40°N, 0930 H) (unfortunately the position of the southern focus cannot be determined) with a well defined flow around it. The main difference in that the time of this focus is notably earlier than for the ‘standard’ $S_q$ system and corresponding to this earlier time there is a broad southward current flow in the early morning hours. The amount of current involved in these flows is quite large. The total northward flow estimated at San Juan is 230 kA and the southward flow estimated at Pilar is 210 kA. The errors in these estimates are of comparable magnitude to that for the Fuquene system.

A possible source for this flow might be the winds which are directly driven by solar heating in the ionosphere and therefore correspond to negative tidal modes. Richmond et al. (1976), Stening (1969) and Tarpley (1970) all show current patterns for modes of this sort which are similar to Fig. 9.

One may note that the sum of the total currents of the 230 kA ‘constant’ and the ‘non ionospheric’ 150 kA systems is greater than the total current for the $S_q$ system in quiet solar years (see Matsushita, 1967b). A comparison of Figs. 6 and 9 shows that the vector properties of the two systems should account for this discrepancy.

8. Conclusions

In this second part of the study of ionospheric current systems the separation procedure has been used to show the subsystems which compose the $S_q$ system. The first of these was associated with the seasonal variations of the electrojet. Certain properties of this subsystem indicated that the source was semidiurnal winds and that the direction of flow was such as to reduce the midday $H$ amplitude at the equator. This system has maximum strength in the solstices with current flow about 100 kA.

The second subsystem was called the ‘Fuquene’. This subsystem appears to be associated with high latitude or magnetospheric processes and there are evidences that it may not flow at lower ionospheric heights at the equator. A method was shown for estimating the strength of this subsystem on the average day and this gave the result for April of 150 kA ±50%.

The third subsystem was the ‘constant’. This is constant in form and amplitude throughout the year. It was obtained by subtracting out the other subsystems. The source of this might be direct ionospheric solar heating. The strength of this subsystem was about 220 kA with possible error as for the ‘Fuquene’ subsystem.

It is particularly the ‘Fuquene’ subsystem which causes the non-correlation of the electrojet with the rest of the $S_q$ system since this system does not effect the strength of the electrojet. Since it is one of the strongest of the subsystems it is particularly important to learn more about its properties. The present type of analysis if used with larger data samples should be able to give more refined pictures of these various subsystems.
The original work on this analysis was done at the University of the West Indies, Kingston, Jamaica where Miss J. Philips did a great deal of the preliminary calculations. The work was continued while the author was a visitor to the Department of Physics, University of Victoria, Victoria, B.C.

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