UT and Day-to-Day Variations in Equivalent Current Systems for World Geomagnetic Variations

Akira SUZUKI

Geophysical Institute, Kyoto University, Kyoto, Japan

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Equivalent current systems of the daily geomagnetic variations are drawn for every two hours throughout the month, December 1964, to investigate universal-time (UT) and day-to-day variations in the middle and low latitude regions. It is confirmed that there co-exist two types of UT variations in the current systems, the regular and the occasional ones. It is also found that the UT variations in the intensities of the northern and southern current vortices are generally in the opposite sense for both the external and internal current systems, though they are sometimes in the same sense. The centers of the northern and southern vortices move in the same direction, coming most northwards at about 10–12^h UT and most southwards at about 02–04^h UT. The harmonic coefficients of the geomagnetic variation show a periodic change with UT, in accordance with the regular UT-dependence of Sq on quiet days. The day-to-day changes at fixed UT's in the intensity and position of the current systems depend systematically on UT. These and other results obtained are discussed in relation to the origin of the regular and occasional variations in the equivalent current systems.

1. Introduction

Geomagnetic variations on quiet days (called Sq) are very regular and their global distribution is usually represented by an equivalent current system of twin-vortex type. Sq has been studied for a long time by a number of investigators since SHUSTER (1889). It has often been pointed out that the Sq changes significantly from day to day, and also from hour to hour. Because of this variability Sq is practically obtained from an average over several quiet days (MAYAUD, 1965). For this reason, recent studies of Sq have been directed to clarify its more detailed features, such as regional, seasonal, daily or hourly character (PRICE and WILKINS, 1963; MATSUSHITA and MAEDA, 1965; GUPTA, 1973, etc.). HASEGAWA and OTA's (1948) work was the first to obtain day-to-day and UT changes in Sq , and then MISHIN and BAZARZHAPOV (1968) and others followed. On the other hand, several attempts have recently been made to represent the world magnetic variations by equivalent current systems or magnetic

potential maps, not only in quiet conditions but also during storms (SUGIURA and HAGAN, 1967a, b; KAMIDE *et al.*, 1976; RICHMOND and VENKATESWARAN, 1971, and others).

SUZUKI (1978, hereafter referred to as paper 1) has recently revised the method of GAUSS (1839) for Sq analysis and made it possible to draw equivalent current systems at a given instant. The method was applied to six quiet days in September 1964 to study UT variations of the geomagnetic field. It was found that the UT variations were composed of two parts, a regular variation and an occasional variation, the former having a tendency to recur every day at the same UT, whereas the latter occurring irregularly for a few to several hours without systematic pattern dependent on UT. The latter is sometimes strong enough to mask the former. Concerning the origin of these two types of variations, we suggested that the former may be caused mainly by the ionospheric dynamo current due essentially to ionospheric winds of thermal origin, and the latter may originate from an occasional solar activity. However, it was difficult to reach any definite conclusion from the analysis of only six days in paper 1.

In this paper we draw the current systems at every two hours throughout the whole month of December, 1964, when quiet days continued fairly long. All the current illustrations and harmonic coefficients are summarized in the Data Book from the World Data Center C2 for Geomagnetism, Kyoto University (SUZUKI and MAEDA, 1978, referred to as Data Book below). In the present paper, the principal results for the UT and day-to-day variations of the equivalent current systems in December 1964 are presented and discussed.

2. Method of Analysis

The method of analysis is essentially the Gaussian one for Sq analysis and some revisions are made as follows (see paper 1 for details):

- 1) Exclusion of the equatorial observatories.
- 2) Use of the three components, (H , D) and (Z) in harmonic analysis.
- 3) Introduction of a weight factor for every station.
- 4) Use of ghost stations in sparse regions.

Among these the use of ghost stations is a key point of the revision. The analysis is divided into two steps: In the first step only a few main harmonics are used to obtain a gross configuration. Values calculated from those harmonic coefficients at several points in the oceanic regions are used as independent data with reduced weight factors in the second step. These points are called here '*ghost station*.' The use of the weight factor in revision 3) is to compensate the uneven distribution of observatories and to adjust the reliability of published data. The method is almost the same as in paper 1. Details as to the data treatment are

Table 1. Details of data treatment.

Items	Treatment	Comparison with paper 1
Observatory	60 observatories between $\pm 60^\circ$ in geomagnetic lat.	Replace Lwiro with Eskdalemuir (035357, $w_2=0.75$)
Harmonics	40 harmonics in all $m=1$ $n=1$ to 8 $=2$ $=2$ to 7 $=3$ $=3$ to 6 $=4$ $=4$ to 5	Same as paper 1
Ghost stations	8 stations	Same as paper 1
Coordinates	Geomag. lat. and local time	Same as paper 1
Datum line	i) Daily mean values ii) Midnight values	i) Same as paper 1 ii) New attempt
Current sheets	At $a=R$	Same as paper 1

summarized in Table 1, and they are also the same as in paper 1 except for the replacement of one observatory.

The magnetic potential V_n at geocentric distance r is expressed as

$$V_n = C + \sum_m \sum_n \left\{ \left(e_{na}^m \frac{r^n}{R^{n-1}} + i_{na}^m \frac{R^{n+2}}{r^{n+1}} \right) \cos mt + \left(e_{nb}^m \frac{r^n}{R^{n-1}} + i_{nb}^m \frac{R^{n+2}}{r^{n+1}} \right) \sin mt \right\} P_n^m(\cos \theta) \quad (1)$$

where C , R , t and θ are a constant, the earth's radius, the local time and the geomagnetic co-latitude, respectively. On the other hand, the surface magnetic variation fields H , D and Z are analysed in the form:

$$\begin{aligned} H &= \sum_m \sum_n (a_n^m \cos mt + b_n^m \sin mt) X_n^m(\theta), \\ D &= \sum_m \sum_n (-b_n^m \cos mt + a_n^m \sin mt) Y_n^m(\theta), \\ Z &= \sum_m \sum_n (a_n^m \cos mt + b_n^m \sin mt) P_n^m(\theta) \end{aligned} \quad (2)$$

with $X_n^m(\theta) = \partial P_n^m / n \partial \theta$ and $Y_n^m(\theta) = m P_n^m / n \sin \theta$. It is well known (see e.g. CHAPMAN and BARTELS, 1940) that the two groups of harmonic coefficients, for potentials (e_{na}^m , e_{nb}^m , i_{na}^m , i_{nb}^m) and for fields (a_n^m , b_n^m , $\mathbf{a}_n^m$, $\mathbf{b}_n^m$), have the following relations:

$$\begin{aligned} e_{na}^m &= \frac{(n+1)a_n^m + na_n^m}{n(2n+1)}, & e_{nb}^m &= \frac{(n+1)b_n^m + nb_n^m}{n(2n+1)}, \\ i_{na}^m &= \frac{a_n^m - \mathbf{a}_n^m}{2n+1}, & i_{nb}^m &= \frac{b_n^m - \mathbf{b}_n^m}{2n+1}. \end{aligned} \quad (3)$$

Then, the current functions (in amperes) of external (J_e) and internal (J_i) origins

are calculated from the magnetic potential by the following relations:

$$\begin{aligned} J_e &= - \sum_n \frac{10}{4\pi} \frac{2n+1}{n+1} \left(\frac{a}{r} \right)^n V_n, \\ J_i &= \sum_n \frac{10}{4\pi} \frac{2n+1}{n} \left(\frac{r}{a} \right)^{n+1} V_n, \end{aligned} \quad (4)$$

where a is the geocentric distance of the current sheets.

Analyses were made for the deviations of geomagnetic field from its daily mean values, and harmonic coefficients and current functions are calculated. In *Sq* analyses, however, local midnight values are often used as a datum line in place of daily means, because of a little current in the nighttime ionosphere. For this reason, the midnight value may be a more appropriate datum line than the daily-mean value. However, the midnight value cannot be used in the present analysis, since the midnight at each observatory is at different UT hour. Although such being the case, we can still obtain an approximate correction to be added when the midnight value is taken as the datum value instead of the daily-mean value, through the mapping of $J_e(\theta, t) - J_e(\theta, 24)$ and $J_i(\theta, t) - J_i(\theta, 24)$ for every latitude. Thus, we have obtained two sets of current systems; (i) current systems for the geomagnetic deviations from daily means, and (ii) current systems with reference to midnight values. These two sets of current systems are calculated at every two UT hours throughout the month of December, 1964, though only a few examples are shown in the present paper (see the Data Book for all other figures).

As mentioned in Introduction (Section 1), December 1964 is a month containing successive quiet days, though not all of them are very quiet. The geomagnetic activity in December 1964 is briefly summarized as follows: From 20th till the end of the month, quiet days continued except for 25th. On the other hand, from 13th to 19th moderately disturbed days continued. From the beginning of the month till 12th, quiet and disturbed days were mixed. The selected days of the month are as follows:

Five quiet days: 5, 12, 27, 30, 31.

Ten quiet days: 2, 5, 10, 11, 12, 22, 24, 27, 30, 31.

Five disturbed days: 7, 13, 16, 17, 19.

Of course, quiet hours may exist even on disturbed days.

3. Results

As an example on quiet days, the external and internal current systems obtained at three UT's (14^h, 16^h and 18^h from the top) on Dec. 31, 1964, are shown in Fig. 1 for the two cases when the geomagnetic variation is defined to

Fig. 1. External and internal current systems for the observed world-wide geomagnetic variations at 14^h, 16^h and 18^h UT on December 31, 1964, where the electric current of 20×10^3 amperes flows between adjacent stream lines. The geomagnetic variation at each station is defined as the deviation from daily-mean values (case i) and from midnight values (case ii).

be the deviation from (i) the daily-mean values and (ii) midnight values, respectively. In the figure the ordinate shows the geomagnetic latitude, and the abscissa shows the local time. The earth rotates under the external current systems from the left to the right. Current contours are drawn at every 20×10^3 amperes. Plus and minus peaks of the current function are marked by the double cross ($\otimes$) and cross ($\times$), respectively. As they are marked automatically by XY-plotter, they do not always show the center of daytime current vortices as seen in the internal current systems. Peak values are also indicated in units of 10^3 amperes. Currents flow counter-clockwise round the positive peak, and clockwise round the negative peak.

December 31, 1964, is one of the international five quiet days of the month, and the current patterns obtained are quite similar to those obtained in usual *Sq* analysis. Two daytime vortices which are very common in the *Sq* current system are seen in all the external current systems shown, though the internal systems are rather complicated. In this example the external systems undergo a slight change from one system to the next, but such variations are usually not small even on quiet days. The variation is usually called the UT variation, though a part of it should be more adequately called the longitudinal variation. For the internal current systems, it has already been pointed out in paper 1 that the currents flow more unsystematically than the external ones and, at the same time, than any other current system derived so far on quiet days. By Figs. 1(i) and (ii) this tendency is confirmed.

On disturbed days the daytime twin-vortex system is considerably modified, and the superior southern vortex conquers or expels the northern one, as shown in a typical example in Fig. 2 for the current system at 06^h UT on Dec. 14, 1964, which is a moderately disturbed day. It is not certain whether the south-

ern vortex expels the northern one also in the other seasons, but we suppose that the reverse will occur in equinoxes or northern summer. It seems that the currents at middle and low latitudes flow mainly in the ionosphere even on slightly disturbed days. However, non-ionospheric currents such as the magnetospheric surface currents, tail currents, ring currents and field-aligned currents of magnetospheric origin may partly be included in the equivalent current systems, whereas the ring currents may be partly excluded because daily mean values are used as a datum line for geomagnetic variations.

4. Discussion

4.1 UT variations

To investigate the UT change of daytime vortex intensities, the northern and southern intensities at every two hours are shown in Figs. 3 (for external) and 4 (for internal), where peak values of the daytime current vortices are plotted upward (for northern) and downward (for southern) directions in an arbitrary unit from the central horizontal line. In some cases especially for

Fig. 3. Progressive change in the dayside vortex intensities of the external currents for case i. The upward and downward distances from the central horizontal line are proportional to the absolute intensities of the current vortices in the northern and southern hemispheres.

Fig. 4. Progressive change in the dayside vortex intensities of the internal currents for case i, with the same way of illustration as in Fig. 3. Occasional blank of data in the northern hemisphere comes from lack of recognizable current vortex in the winter season.

the internal current systems, the daytime vortices cannot be found in the current diagrams, because the intensity is too weak or the vortices do not exist at proper positions. In the first case the intensity can be derived from the original chart of current functions which is used to draw current maps, but in the second case blanks are left in Figs. 3 and 4. In both figures, the southern hemisphere currents are much stronger than the northern, and this is quite natural in December, the northern winter month.

For the external current systems, it is distinct that the northern intensity becomes maximum at about 18^h and minimum at about 06^h UT. For the southern, the maximum is around 06^h and minimum is around 18^h in many cases, but in some cases the maximum occurs at about 18^h and minimum at about 06^h UT. From these results, it may be said that the intensities of the northern and southern current systems generally change in the opposite sense, i.e. when the northern vortex becomes intense, the southern becomes weak and when the northern vortex becomes weak the southern becomes intense. For some days, however, the reverse is true, i.e. the intensities of the two vortices change in the same sense. For this problem, HASEGAWA and OTA (1948) and MISHIN and

BAZARZHAPOV (1968) have obtained different results from the data in the II Polar Year and the IGY, respectively, the former saying that the change is out-of-phase (see Fig. 7 for HASEGAWA and OTA, 1948) and the latter in-phase. The present results agree with the former, including the time of peak intensities in many cases. For smaller cases, however, Mishin *et al.*'s conclusion cannot be rejected, though the peak hours in the present results are several hours later than those by theirs (12–15^h UT).

As the internal current vortices are often vague in the northern hemisphere or complicated as a whole, their intensities cannot be determined accurately as in the external ones. Generally, however, it can be said at least that main features of the external current systems are roughly reflected in the internal systems. The out-of-phase tendency in the northern and southern intensities is seen in Fig. 4.

The UT change in the latitudinal position of the centers of the daytime current vortices is shown in Figs. 5 and 6 for the external and internal systems, respectively. The plots scatter rather irregularly especially for the internal systems, since the vortices are often not set up in a clear form. Still, certain tendencies can be read from the figures. For the external figures, the locations

Fig. 5. Progressive displacement of the vortex centers of the external currents in December 1964. The ordinate indicates the geomagnetic latitude. Each circle shows the location of the vortex center at two-hour intervals. When the locations cannot be determined or the vortices are absent, the circles for such times are omitted.

Fig. 6. Progressive displacement of the vortex centers of the internal currents in December 1964, with the same way of illustration as Fig. 5.

of the northern vortices around 06^h UT are exceptional, since the northern vortices are often weak in these hours (see Fig. 3) and expelled into the polar regions. An example of the current system on such conditions is seen in Fig. 2. Such features are seen even at other hours in disturbed conditions, and on the contrary the feature is seldom seen after Dec. 20, when quiet days continue. On quiet days the locations of the northern vortices at 02–06^h UT are at lower latitudes, and thus features in these hours are quite different between quiet and disturbed days. Generally, if the discussion is restricted to quiet days only, the location of the northern vortex is most equatorwards at 02–04^h UT and most polewards at 10–12^h UT, and that of the southern one is most equatorwards around 12^h UT and polewards around 18–04^h UT. For the internal vortices, the location is more complicated as compared with the external case. However, the feature of the external vortices is very roughly reflected in the internal vortices, especially on quiet days after Dec. 21. On the average, both centers in the internal system seem to be slightly northwards than in the external system.

As to the UT variation of the *Sq* vortex locations, two earlier results by HASEGAWA and OTA (1948) and MISHIN and BAZARZHAPOV (1968) are similar in respect that the two vortices show parallel movements. The analysis by GUPTA (1973) for eight most quiet days shows the same conclusion, if the locations given in geographic latitudes are converted into geomagnetic latitudes at local

noon. As the tendency is generally true also in the present results, the parallel tendency is common in these four results. However, there is a slight difference among the four papers regarding the time dependence of variations. Mishin *et al.* reported that the maximum geomagnetic colatitude was at 16.5^h UT, but in the present results it is the second peak, and the maximum occurs at 02–04^h UT.

Fig. 7. Average UT variations of (a) the intensities and (b) center latitude of the current vortex for the geomagnetic S_q variation over ten international quiet days in December 1964. For the external currents, an average for the five quiet days is also shown by broken lines, and the results by HASEGAWA and OTA (1948) by circles connected by solid lines, respectively. For Hasegawa and Ota's curves, the ordinate should be read as potentials in units of 10^3 cgs.

Gupta's result is quite similar to the present one including also the minimum around 10–12^h UT. OTA (1950) showed that the maximum was around 04^h, but contrary to others the minimum around 16^h UT.

The average intensities and latitudinal locations of the vortex centers for the international ten quiet days are calculated at every two hours and are shown in Fig. 7. For the external systems, the averages for the international five quiet days and the results by HASEGAWA and OTA (1948) are also shown by the thin broken lines and solid lines connecting the circles, respectively. As Hasegawa and Ota used the surface integral method to obtain the potential distribution, the separation between the external and internal parts was not made. For their results, the current intensity in the ordinates should be read as a potential value in unit of 10⁹ cgs. In the present analysis, the variation mode mentioned above, i.e. an anti-phase relation between the northern and southern intensities and a parallel tendency between the external and the internal ones, are all confirmed fairly well. For the latitudinal locations, the situation is different for the external and internal current systems, and whereas the external locations agree well with the already mentioned tendencies, the internal ones do not. Parallel movements of external two vortices are quite convincing. As mentioned above the external southern vortex is most polewards around 18–04^h UT, but in the average figure the maximum poleward shift takes place at both 18^h and 04^h UT. For the internal locations the average curves seem to have a little significance because of the large fluctuations on individual days.

The international ten quiet days naturally contain slightly more disturbed intervals in comparison with five quiet days. It is seen in Fig. 7 that the geomagnetic disturbance decrease the northern current intensities, but increase the southern ones. The northern vortex generally shifts slightly northwards during the disturbed interval, but the southern vortex seems uninfluenced. The reason of this behavior is not clear and we only imagine that a small amount of field-aligned currents flow from the winter to the summer hemispheres on less quiet days than on extremely quiet days, and they slightly intensify the summer vortex which may push the winter vortex polewards. This amount is, however, only a little.

In paper 1 it has been pointed out that two types are coexisting in the UT variations on quiet days. One of which, the regular variation, is very clearly ascertained in the present analysis, because the harmonic coefficients show very interesting periodic tendencies. The monthly mean UT variations for main field harmonics (a_n^m , b_n^m , a_n^m , b_n^m) appeared in Eq. (2) are calculated and plotted in Fig. 8. To make the periodic tendencies clear, each curve is expressed by a Fourier series as

Fig. 8. Monthly mean UT variations of the spherical harmonic coefficients ($a_n^m, b_n^m, a_n^m, b_n^m$) of the geomagnetic field in December 1964 for the terms of $m=1, n=2$ (bold solid lines), $m=2, n=3$ (broken lines) and $m=3, n=4$ (thin solid lines). The ordinate is given in units of gammas ($1 \gamma = 1 \text{ nT}$). Note here that the scale for a_n^m is twice the others.

$$a_n^m(T) = c_0 + \sum_{k=1}^6 c_k \cos(mT - \varepsilon_k) \quad (5)$$

where k at which c_k becomes maximum ($=c_{\max}$) gives the prevailing period of each UT variation and c_0 gives an average magnitude of each coefficient. The ratio $|c_{\max}/c_0|$ gives a measure whether a coefficient is stable or periodic with UT. These three parameters are summarized in Table 2. In the table, the time is given at which the absolute value of each coefficient becomes maximum or minimum. Furthermore, in the last column of the table some remarks are given on the characteristic features of each coefficient noticed in the original two-hourly curves in the Data Book. The peak hours are also determined from the original curves so that a peculiar tendency is not overlooked by taking an average.

Table 2. Monthly-mean UT-dependence of the spherical harmonic coefficients of the geomagnetic Sq variation. 'Max.' and 'Min.' are defined for absolute values of coefficients.

Coefficients	Prevailing periods (days)	c_0	$ c_{\max}/c_0 $	Peak hours (UT)		Remarks
				Max.	Min.	
a_2^1		14.7	0.08			Largest, stable and non-periodic
a_3^2	1	-11.0	0.28	18	04-06 or 12	
a_4^3	1	5.4	0.48	18-06	10-12	
b_3^1	(1/2)	-4.6	0.35	2-4	12 or 18-20	Sensitive to disturbance
b_3^2	1	1.7	1.70	10, 14-16	22-4	Diurnal but two maximum hours
b_4^3	1, 1/2	-1.5	1.10	4, 14	10, 22	
a_2^1	1/2	3.5	0.81	10, 20	02, 14	10 ^h and 14 ^h are times of principal max. and min.
a_3^2	(1)	-3.6	0.36	16-20	02-06	Changeable even on quiet days
a_4^3	1/2	1.8	0.59	4-6, 16	8, 22	
b_3^1	1/2	-1.2	1.30	8, 18	12, 24	Sensitive to disturbance
b_3^2	1	-0.2	11.00	10	18-22	Varies around zero
b_4^3	1/2, 1/4	0.6	1.50	(2, 18)	(24)	Varies around zero

It is very interesting that the largest term a_2^1 is almost non-periodic and stable as indicated by the exceptionally small value of $|c_{\max}/c_0|$. Other a_n^m 's have a somewhat similar tendency on the whole. On the contrary, b_n^m 's have small values of c_0 and oscillate around zero, especially as b_3^2 does. The contribution to the UT variations can be estimated by the amount of $c_{\max}$ which is not shown in the table, but can be calculated by $c_0 \times c_{\max}/c_0$. The value is larger for a_3^2 , a_4^3 , b_3^2 , a_2^1 , b_2^1 and b_3^3 , though any systematic relation is hardly found among them. It is quite natural as is known in Sq studies that on the whole the cosine terms, a_n^m 's and a_n^m 's, are larger than the sine terms, b_n^m 's and b_n^m 's, respectively. The vertical-field coefficients are more changeable and sensitive to the magnetic disturbance than the horizontal-field coefficients. Diurnal and semidiurnal changes occur with a similar frequency. Though it is not seen in the average curves, there are some coefficients which are especially sensitive to magnetic disturbance; such as b_2^1 , a_2^1 and b_2^1 . This agrees with RASTOGI and IYER (1976) who have shown that the diurnal component is much more sensitive to the solar activity than other terms.

The corresponding figure and table for the principal potential coefficients (e_{na}^m , e_{nb}^m , i_{na}^m , i_{nb}^m) are given in Fig. 9 and Table 3, respectively. For the external coefficients the largest term e_{2a}^1 is again most stable, but it is slightly periodic in contrast to a_2^1 . This is quite natural, because e_{2a}^1 is obtained from a_2^1 and a_2^1 by Eqs. (3). On the whole, the cosine terms, e_{na}^m 's and i_{na}^m 's are less periodic with

Fig. 9. Monthly mean UT variations of the potential coefficients (e_{na}^m , e_{nb}^m , i_{na}^m , i_{nb}^m) for the terms of $m=1$, $n=2$ (bold solid curve), $m=2$, $n=3$ (broken curves) and $m=3$, $n=4$ (thin solid curves). The ordinate is given in gammas.

UT than the sine terms, e_{nb}^m 's and i_{nb}^m 's. The contributions to the UT variations from the four diurnal and semidiurnal terms are larger than those from others as estimated from $c_{\max}$. Among the internal coefficients, i_{2a}^1 is by far the largest and is most stable. There is almost no difference among six coefficients as to the contributions to the UT variations.

4.2 Seasonal variation

For seasonal variations of Sq current intensities, it is usually accepted that the vortices in equinoxes are almost equally intense as those in summer, and the intensities in equinoxes and summer are much greater than in winter (MAEDA, 1968; SUZUKI, 1973). On the other hand, for seasonal variations in latitude of current centers, earlier results are different from one another, and they seem to be classified into two groups. SHIRAKI (1972) and MATSUSHITA (1960) studied the data in solar active years in the West Pacific and North American regions,

Table 3. Monthly-mean UT-dependence of the potential coefficients for the geomagnetic Sq variation. Absolute values are used to calculate $c_{\max}/c_0$ and peak hours also are given for absolute values of coefficients.

Coefficients	Prevailing periods (days)	c_0	$ c_{\max}/c_0 $	Peak hours (UT)		Remarks
				Max.	Min.	
e_{2a}^1	1/2	5.1	0.14	10, 20	14	Largest and most stable
e_{3a}^2	1	-2.6	0.27	4-6	18	
e_{4a}^3	1	1.0	0.42	4, 18	12, (24)	Often semidiurnal
e_{2b}^1	1/2	-1.6	0.44	6, 16	12, 20	Large at disturbed hours
e_{3b}^2	1	0.3	3.00	10	24	Very regular curve
e_{4b}^3	1/2	-0.2	2.00			Small
i_{2a}^1	1/2	2.3	0.22	4, 16	12	Most stable among internal coefficients
i_{3a}^2	1	-1.1	0.36	24	12	
i_{4a}^3	1	0.4	0.75	6, 18	12, 24	Often semidiurnal
i_{2b}^1	1/2	-0.6	0.46	4, 16	10, 20	
i_{3b}^2	1/3	0.3	1.00	8, 16, 22	2, 10, 20	Small but clear terdiurnal variation
i_{4b}^3		-0.2	0.80	2, 14	6, 22	Diurnal, semidiurnal, small

respectively, and they concluded that vortices were located at higher latitudes in summer than in winter. SUZUKI (1973) obtained a roughly similar conclusion, but as his analysis was made independently for three zones, minute differences were seen for each zone as described later again. On the other hand, BARTELS (1928), OTA (1950) and HASEGAWA (1960) who analyzed data in solar quiet years obtained the results that the vortices were at lower latitudes in summer than in winter and equinoxes. SHIRAKI (1972) inferred that this discrepancy between two groups would be due to the difference in solar activities at the time when the data were used rather than the difference in statistic and analytical methods.

To investigate the seasonal variations in the present method, the average locations and intensities of external vortices on the five international quiet days are compared between December (in this paper) and September (in paper 1) in the same year 1964. The results are shown in Figs. 10(a) and (c). For locations, it is seen in Fig. 10(a) that both the northern and southern vortices are generally situated polewards in December than in September. This result is inconsistent either with the first group or the second, considering that December is in northern winter and southern summer. However, the relation of two curves in Fig. 10(a) is found to be in good agreement with the result by SUZUKI (1973). In Fig. 10(b) focus positions obtained for three zones by SUZUKI (1973) are reproduced into UT variations on a simple assumption that the focus is located in

Fig. 10. (a) UT variations in the center latitude of the current vortices for September and December 1964. (b) UT variations in the dip-latitude of the vortex centers by SUZUKI (1973). (c) UT variations of the current intensities in September and December 1964.

the noon meridian. Common tendencies are easily seen between Figs. 10(a) and (b) concerning the relations of two seasonal locations. The analyses in this paper and in paper 1 are based on data in the solar minimum year, whereas those by SUZUKI (1973) were based on IGY data (solar maximum years). Though the comparison was made between two curves derived from only five days, it can be said that the seasonal variations of the central latitudes have some dependence on UT. As to the seasonal change of current intensities (Fig. 10(c)), the tendency is clearly seen that the intensities in summer and equinox are much greater than those in winter. In the southern hemisphere, however, the intensity difference between equinox and summer is considerably larger than the previous results.

4.3 Day-to-day variations

The day-to-day variation is studied with the external current systems on consecutive quiet days from Dec. 20 to Dec. 31, 1964. The current intensities and vortex locations are rearranged from Figs. 3 and 5 for every two fixed hours as shown in Fig. 11. In the figure the intensities and vortex latitudes are shown without regard to the sign in the upward (for the northern) and downward (for the southern) directions from the central bar, similar to the illustrations in Figs. 3 and 5. Dec. 20 to Dec. 31 are ordered from the left to the right in each block. In the figure the variation with the period of 7 to 10 days are clearly seen, both in the intensity and locational changes. The results may correspond to that of SHIRAKI (1974) who examined the data in the West Pacific regions and showed that the vortex latitudes and intensities vary with a period from about 10 to 30

Fig. 11. Day-to-day changes in the intensities and center latitudes of current vortices at fixed UT's during 20-31 December 1964 (from the left to the right). The intensity and geomagnetic latitude of the current vortex in the northern and southern hemispheres are plotted upward and downward from the central horizontal lines, respectively.

days as well as with a period of a few days. He also showed that the current locations had, in the frequency analysis, a tendency to vary with a period of 7, 10, 17 and 33 days. In the present result, the variation with the period of 7 to 10 days are more distinct in the intensity change than in the locational change, and it seems to undergo a phase shift with UT.

On the other hand, the increment from one day to the next can be calculated from Fig. 11 at every two fixed hours and is shown in Figs. 12 and 13 for the intensities and central latitudes, respectively, where the positive and

Fig. 12. The left two columns show the increase or decrease in the external current intensities at the given UT hours in the southern and northern hemispheres on consecutive days from 20 to 31 December 1964 from the left to the right. The ordinate is the difference in the current intensities on consecutive days; white and black columns denote the increase and decrease, respectively. The right column shows the average day-to-day variability in the current intensities, regardless of increase or decrease in the current intensity.

Fig. 13. The left two columns show the day-to-day variability in the latitude of current vortex centers at the given UT's in the southern and northern hemispheres from 20 to 31 December 1964; open and full circles are for the southward and northward shift in the latitude of vortex center after one day, respectively. The average in the right column is shown for the mean absolute value of the day-to-day variability on consecutive days.

negative values are shown by the open and shaded columns in Fig. 12 and by the open and full circles in Fig. 13. Although the day-to-day variation is rather random in each hour block both for the intensity and latitudinal changes, there seem to exist some tendencies which depend on UT which are clearly seen on the right-hand side of Figs. 12 and 13 in the average day-to-day variation, where the average was made without regard to the sign. For the northern system, the day-to-day inequalities in the intensity are small around 08–14^h UT and large around 16–04^h UT, whereas those in the location are large around 04–10^h and small around 12–02^h, indicating a negative correlation between the intensity

and location. For the southern hemisphere, however, the day-to-day variability in the intensity is large around 06–14^h UT and small around 16–04^h UT, roughly indicating a positive correlation with the location. Both for the northern and southern hemisphere, the day-to-day variation is generally small when the vortex is located at higher latitudes (see Fig. 7).

The effect of the IMF sector polarity on the vortex location was studied by MATSUSHITA (1975) and SHIRAKI (1977). Matsushita showed that the vortex location shifted by 4° to the poleward or equatorward as the polarity was away from or toward the sun in summer in the northern hemisphere. Shiraki confirmed this conclusion, though the shift was estimated to be smaller. In December, 1964, one of the passages of sector boundaries across the earth was in the early morning on Dec. 26 (WILCOX and COLBURN, 1972), the day at the middle of the continuous quiet conditions, the sector being away from the sun before the passage and toward the sun after it. As is seen in Fig. 5, the centers of external northern vortices seem to be located slightly equatorwards in the period of the toward-sector than in the away-sector, but the present result is not so reliable as to distinguish such a small movement.

4.4 *Regular and occasional variations*

In paper 1, we have defined two parts of the UT variations in equivalent current systems on quiet days, i.e. the regular variation and the occasional variation. Various kinds of disturbances seem to be added to those current systems on disturbed days and they contaminate the quiet variation, though the degree of the contamination differs for different days. The regular variation is defined as such that it occurs on every day repeatedly at the same UT. The feature is revealed in the recurrent tendency of the spherical harmonic coefficients of the geomagnetic variation. On the other hand, the occasional variation is defined as the variation which occurs irregularly and plays an additional role to the regular variation, even though the occasional variation sometimes overcomes the regular variation. The day-to-day variation is considered to be a typical example of the occasional variation, for it appears just as a deviation from the recurrent tendency. The occasional variation differs from the disturbed one by the fact that it appears on quiet conditions and quiet days, and magnetograms at that occasion show smooth curves.

The occasional variations are seen everywhere in the present analysis as is shown by frequent irregular time-variations in Figs. 3 to 6. Among them one of the typical examples occurring in the quiet conditions is seen at 06–14^h UT on Dec. 30, 1964, in the southern current system which is exceptionally weak compared with the other days. The contrast between this and the large intensity on the next day yield an enhancement of the day-to-day increment (see Figs. 11

and 12). As is seen in this example, the occasional variation sometimes lasts for a few to ten hours. However, another kind of occasional variation often occurs at only a certain UT and continues for several days. The external current pattern at 14^h on Dec. 25, 1964, is a case in point. The pattern is quite different from the preceding and following two patterns at 12^h and 16^h, but it appears, as shown in Figs. 14(a) and (b), repeatedly till 28th leaving weak after-effect for some more days (compare with corresponding current systems in Fig. 1(i)).

As well known, the magnetic variation observed on the ground are caused by electric currents in space around the earth and their induced parts within the earth. The external currents for regular geomagnetic variation may be mainly attributed to the ionospheric dynamo currents and partly to the magnetospheric currents (OLSON, 1970). For the main cause of the regular UT variation, our

Fig. 14. External current systems at 14^h UT on (a) December 25 and (b) December 26, 1964.

results may support an interpretation by the dynamo theory (NAGATA and SUGIURA, 1948) by taking the disagreement between the geomagnetic and rotation axes of the earth into consideration. For the occasional variations, various causes can be considered, since the time of occurrence and the feature of phenomena are usually quite irregular. Among them, the solar wind seems to be one of the plausible causes, because the solar wind induces various kinds of electric currents in the magnetosphere in which the field-aligned currents and partial ring currents may be most effective in producing ground magnetic variations. Another plausible cause may be an irregular change in the neutral wind in the ionosphere perhaps due to a change in the tidal oscillation of thermal origin. To clarify these problems, more observations not only on the ground but also in space above the ionosphere are required in the future (see paper 1).

December is a month of northern winter when the southern current vortices are superior to the northern ones. The tendency is very clear in almost all the figures without exception. The choice of this month, however, may not be adequate for the study of world geomagnetic variations, because the distribution of observatories is not sufficient in the southern hemisphere where the superior vortices are located, and therefore the reliability of the analysis is lessened as the whole. Especially at higher latitudes in the southern hemisphere, anomalously intense currents often appear. This seems mostly to be caused by data at Macquarie Island which is only one and important observatory in this area and is often disturbed because it is located near the auroral zone. The results obtained are, however, convincing enough to merit the discussion given above. At the same time, similar analyses in equinox or northern summer under quiet conditions are required in the future.

5. Conclusions

Suzuki's method (see paper 1) of instantaneous analysis for the global distribution of the magnetic fields is applied to the data in December, 1964 when magnetically quiet days continued for many days, and the equivalent current systems are drawn at every two hours through the month. Using these current systems, together with the original distribution of current functions, the UT and day-to-day variations of the current systems are studied, and the following conclusions have been obtained.

- 1) It is confirmed that there are two types of variations in the UT variation on quiet days, the regular and the occasional variations, as has already been proposed in paper 1. On disturbed days some disturbed variations are added to these.

- 2) The intensity of the northern and southern current vortices vary in

the opposite sense in many cases, but less often they change in the same sense. The northern maximum generally occurs at 18^h and minimum at 06^h, and the situation is reversed for the southern systems. For latitudinal locations the two northern and southern vortices move in the same directions to the north or to the south, coming most northwards at about 10–12^h UT and southwards at 02–04^h UT. These tendencies of the external current systems are roughly reflected to the internal current systems.

3) The coefficients of spherical harmonic expansion of the geomagnetic field show distinct periodic variations with UT. For the field coefficients, a_2^1 is largest and most stable. Generally a_n^m 's are stable and b_n^m 's are mostly periodic. Large contributions to the UT variations are made by the terms a_3^2 , a_4^3 , b_3^2 , a_2^1 , b_2^1 and b_3^3 . For the potential coefficients, the sine terms are more periodic than the cosine terms. For the contribution to the UT variation, four diurnal and semi-diurnal terms are comparatively large in the external components and almost no difference is found among six internal coefficients.

4) Under slightly active conditions the summer vortex is enhanced and push the winter vortex, which is weakened at the same time, to the poleward.

5) For the seasonal change it is found that the intensity of the current vortex becomes weaker in the order of summer, equinox and winter. The seasonal variations in the latitude of vortex centers differ at different longitudes and the variation mode agrees well with that found already by SUZUKI (1973).

6) For the day-to-day variation, the variation with the period of 7 to 10 days is noticeable. The day-to-day variation in the intensity is small for both the northern and southern vortices when they are located at higher latitudes.

7) A slight difference in the position of vortex centers seem to appear at the passage of the IMF sector boundary, but it could not be confirmed as an effect of IMF.

8) Two types of occasional variations are mentioned. One is a one-day phenomenon which occurs occasionally and persists for several hours. Another is a phenomenon which occurs only at certain fixed hours over several days.

9) The cause for the regular and occasional variations are considered. The former may be caused by the dynamo currents in the ionosphere, and the latter may be caused partly by the solar wind and partly by the ionospheric wind. However, more observations of magnetic fields especially in space above the ionosphere are very much required to make clear the causes of ground magnetic variations.

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