Long Time Variations of the Attenuation Constant and the Zero-level of Dst inferred from Variations of the Geomagnetic Horizontal Component observed at Kakioka

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Abstract

The geomagnetic horizontal component H increases after a disturbance to the next, reflecting a decline of Dst-field. The quiet day occurs in the course of the H-increase. Daily mean values of H for a successive occurrence of the quiet day shows the increase is exponential, suggesting a possibility to find the final level of the H-increase, that is the zero level of Dst. However the analysis to find the final level from a single H-increase is not easy because of noises included in the daily mean value of H, for example day-to-day changes of the diurnal variation, solar wind compression, minor disturbance and the base line value of the variometer. Some statistical treatments are neccessary.

Quiet days are newly selected by a common criterion for disturbance activity instead of that of the international calm day which is not equal for each month. The present analysis uses average H variations observed at Kakioka for the cases that the quiet day occurs successively for 4 days. The result shows an interesting long time variation of the attenuation constant of the H variation. After the middle of 1950's the attenuation constant increases linearly compared with the invariability before the epoch. A magnetospheric pollution due to human activity might be a cause of the increase. The zero level of Dst is higher by 10–30 nT than the quiet day mean. The long time variation of the difference of about 20 nT includes two components originating in the variations of the attenuation constant and the intensity of the disturbance. Excluding the two components the residual shows a '60-year period variation' of 10 nT. The cause of the 60-year period variation remains to be studied together with the cause of the increase of the attenuation constant after 1950's.

1. Introduction

It is desirable to know geomagnetic fields free from disturbances of external origin to study the internal earth magnetic field or disturbances, particularly their long time variations. The secular variation of the geomagnetic field is usually expressed by the variation of all day mean of the observed field. Nevertheless it is clear that the all day mean includes disturbance fields. A better choice may be the calm day mean. However the calm day mean also includes a part of disturbance fields, particularly a decrease of the horizontal component H, produced in the preceding disturbed period. The disturbance field of H-decrease declines slowly after the period, influencing the mean value of H on a calm day which occurs a few or several days after the disturbed period. The variation of H is known as Dst, which appears clearly in a magetic storm. Many disturbances smaller than storm have a similar variation.

Equatorial ring currents are considered to be the cause of the Dst including the similar variation of smaller disturbance. The decline of the disturbance field of H-decrease expresses a decay of equatorial ring currents produced by the disturbance. From a disturbance to the next H increases gradually reflecting the decay of the equatorial ring currents. This fact suggests that an analysis of the increasing process of H may give an estimate of Dst0 which means the H-value at Dst=0. Dst0 must be larger somehow than the daily mean value of H on a calm day between the disturbances. But the analysis to obtain the Dst0 is not easy because smaller disturbances occur frequently shortening calm periods and because many kinds of noise contaminate the H even in the calm period. Then statistical treatments such as superposition of many cases are necessary. The average variation obtained by superposition is nearly exponential, that is exponential decay of disturbance field.

The analysis are made using daily mean values of H at Kakioka, giving estimates of the attenuation constant, A, of the exponential decay and Dst0. The estimated values of A and Dst0 show the interesting long time variations.

2. Average variation of H during calm period

The exponential increase of H can be noticed sometimes in a long chain of quiet day. But even on the quiet days several kinds of noise contaminate the H-value obscuring the change of H. Then the values of the attenuation constant A and the Dst0 estimated from such an individual case are generally not so accurate. Some of the noises are day-to-day changes of the diurnal variation, minor disturbance, compression of the solar wind and the unstable base line value of the variometer. To reduce the noise effect a better way is a statistical treatment of superposition for many cases of successive occurrence of the quiet day. When N international calm days occur successively the case is denoted here by NQ-case, where the international calm day is one of the 5-quietest days selected for each calendar month.

Fig. 1 shows the average variation of daily mean value of H at Kakioka obtained by superposing 4Q-, 3Q-, 2Q- or 1Q-case for 64 years from 1925 to 1988. Numbers of 4Q-, 3Q-, 2Q- and 1Q-case are 67,213,531 and 1301, respectively, except the cases which include no data period. 5Q-case is rare. All H values are expressed by deviations from the daily mean value of the first calm day which is the time origin as the epoch of superposition. H-values for 8-days around the calm day are shown numerically in Table 1 to compare each case precisely.

The daily mean value of H is low before the first calm day reflecting the effect of disturbances. The H-value increases exponentially during calm days. After the last calm day the value begins to decrease again reflecting the effect of the next disturbance. At the time end of the figure 27-day reccurrences are also found.

The increase of H during calm days is very close to an exponential variation which begins at the day before the first calm day. Suppose the final level E_0 of H-value expressed

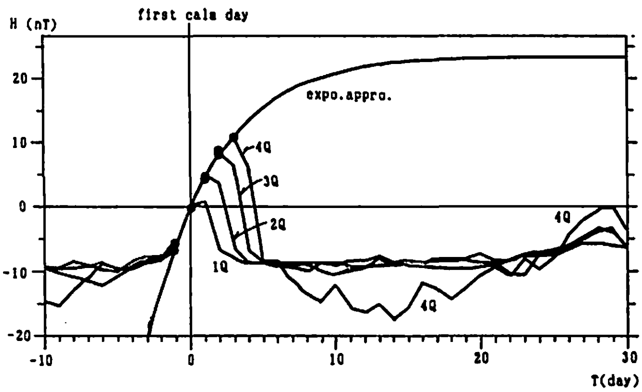

Fig. 1 Average variations of the geomagnetic horizontal component H at Kakioka for 41-days around the international calm day of 1925-1988 and the exponential variation approximating to 4Q-case.
4Q, 3Q, 2Q and 1Q represent the cases that the international calm day continues for 4,3,2 and 1 days, respectively. Expo. appro. denotes the exponential variation approximating to 4Q-case. The time origin, $T=0$, is the first calm day and all H-values are expressed by the deviation from the value at $T=0$. Dots express H-values of the calm days and the day before the first calm day. Those H-values are shown numerically in Table 1 because it is difficult to show by separate dots in the figure for each case.

Table 1 Numerical values of the average H variations shown in Fig. 1 for 8-days around the international calm day. Underlined values are those for the calm day. Meanings of 4Q, 3Q, 2Q, 1Q and expo. appro. are the same as Fig. 1.

T, day	-1	0	1	2	3	4	5	6
	nT	nT	nT	nT	nT	nT	nT	nT
1Q	-6.5	<u>0</u>	0.8	-6.5	-7.9	-8.5	-8.5	-8.6
2Q	-5.6	<u>0</u>	<u>5.1</u>	3.7	-6.2	-8.7	-8.7	-8.2
3Q	-5.5	<u>0</u>	<u>4.7</u>	<u>8.8</u>	6.5	-6.7	-8.8	-9.2
4Q	-5.6	<u>0</u>	<u>4.5</u>	<u>8.1</u>	<u>11.1</u>	5.9	-8.3	-8.5
expo. appro. to 4Q	-5.59	-0.02	4.49	8.14	11.08	13.46	15.38	16.94

Attenuation constant $A=0.213\ (\mathrm{day})^{-1}$, Final level=23.48 nT by the deviation from the value of the first calm day, the attenuation constant A and the time T whose zero is the first calm day, the average H variation $E(T)$ is expressed by,

$$E(T) = E_0 - E_0 \exp(-AT), \qquad (1)$$

for $T = -1$ to N. The constants E_0 and A are estimated from the average variation $E(T)$ so as to minimize the square error. For 4Q-case the estimated values of the constants and the calculated $E(T)$ are shown in Table 1 and Fig. 1. Differences between the observed and calculated values are so small that the exponential decay (1) is a good approximation of the H variation beginning with the disturbed field $E(-1)$.

If the H of each individual case varies exponentially with an invariable common attenuation constant, the average H variation is exactly exponential. Even when the attenuation constant is variable, the estimated value of the attenuation constant of the average variation is not so different from the mean value of the attenuation constant of the individual case and the estimated final level E_0 is very close to the mean value, as discussed in the latter section 3.2.

If nighttime values of H are used instead of the daily mean values, noises coming from the day-to-day change of the diurnal variation may be reduced. But minor disturbances, which occur still on quiet days may enhance the noise in the nighttime. Such an enhancement can be noticed in the diurnal variation of K-index, at least at Kakioka (Yumura, 1951). Using the daily mean values, such noises are reduced by averaging for 24 hours.

3. Long time variation of the attenuation constant

Whether the attenuation constant is variable or not, it is difficult to know from individual cases because of noises which occur still on quiet days. Even if a long chain of quite quiet days are found and a beautiful exponential change of H is seen, proof of no noise is generally difficult. Some statistical procedures must be necessary to know a variation of the attenuation constant if it exists. For the statistics the use of the international quiet day, Q, is not better because 5 days are regularly selected for each month notwithstanding the difference of activity between months. It is better to use a criterion of quiet day not restricted by the frame of month.

The new criterion of quiet day here used is that aa-index is smaller than 12 and the half-day value of the index is smaller than 15. In order to select the quiet day going back to long past, aa-index is used. Q_a denotes the quiet day based on the new criterion. Many of Q, for example 16% of the total in a sunspot cycle from 1954 to 1964, have a higher activity exceeding the upper limit of Q_a. That means the new criterion gives a rather severe condition for the quiet. Nevertheless Q_a's are found more frequently than Q's, bringing numerous cases of successive occurrence of the quiet day.

Superposing statistics are made here for $4Q_a$-case which means the case of 4 successive Q_a's. Mean occurrence frequency of the $4Q_a$-case is 5.8/year compared with 1.4/year of 4Q-case for 1951-1981, which is the data period of the analysis in the next section 3.1. The disturbance activity of the $4Q_a$-case is not in general higher than that of 4Q-case. For example two 4Q-cases and five $4Q_a$-cases are found in 1958 having the mean aa-indeces of 9 and 7.5, respectively.

Considering the statistical reduction of noises, a period of one year will be too short to estimate the attenuation constant accurately from the average H variation of $4Q_a$-case in the period. More than a few years may be necessary. From the averages of a few years or more it may be possible to obtain the solar cycle dependency together with the long time variation of the attenuation constant.

3.1 No dependency of the attenuation constant on the solar cycle

In order to get a better estimate of a time variation of the attenuation constant, daily mean values of H from 1951 to 1981 at Kakioka are analysed at first. The stability of the base line value of the variometer has increased much at Kakioka since 1951 using a temperature compensation device developed by T. Kuboki (1951). And after 1981 $4Q_a$-case is rather rare.

Fig. 2 shows attenuation constants estimated from the average H variatin of $4Q_a$-case in each half of a solar cycle from 1951 to 1981. One half is the active period whose yearly mean sunspot number is larger then 80, and the other is the calm period less than 80. The time coordinate of the dot in the figure is the center of the respective period. At a glance it is known that a linear increase of the value of the attenuation constant is remarkable and that the value does not depend on the solar activity level.

Considering the variable attenuation constant before discussing the interesting long time variation, a meaning of the approximation by an exponential variation for the average of H variations having variable attenuation constants should be investigated.

3.2 Exponential variation approximating to the average of H variations having variable attenuation constants

The average of exponential variations is, strictly speaking, not exponential if the attenuation constant is variable. But it will be expected that the average is nearly exponential if the range of the variable attenuation constant is not so wide.

Provided that the i-th H variation is expressed by an exponential variation,

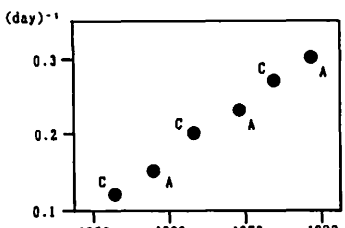

Fig. 2 Attenuation constants of the average H variation of $4Q_a$-case for each half a solar cycle of 1951-1981. A and C denote active years (sunspot number >80) and calm years (<80), respectively. $4Q_a$-case represents the case that the newly selected quiet day occurs successively for 4 days (see text).

$$E_i(T) = F_i - G_i \exp(-A_i T), \tag{2}$$

the average of the variations for $i = 1, 2, \ldots\ldots, n$ is supposed to be nearly equal to an exponential variation,

$$E(T) = F - G \exp(-AT). \tag{3}$$

The final level F, which occurs when T tends to ∞, differs from the mean of F_i by ΔF. The difference ΔF comes from the approximation of the average of the exponential teams. The mean of F_i is included equally in the both of the average variation of $E_i(T)$ and the exponential variation $E(T)$. Then there is no need to consider the F_i's in the estimate of ΔF and A.

Considering random distributions of G_i and A_i, the differences ΔF and ΔA are calculated for several ranges of distribution of the attenuation constant, where ΔA means the deviation of A from the mean of A_i. Twenty individual exponential variations, $-G_i \exp(-A_i T)$, $i = 1 - 20$, with different random values of G_i and A_i are averaged, and an approximate exponential variation, $\Delta F - G \exp(-AT)$, is estimated by the least square method for $T = 0 - 4$. Here the origin of the time T is not the first quiet (calm) day but the day before the first quiet (calm) day. For 100 different random distributions mean ratios of ΔF to the mean value of G_i and mean ratios of ΔA to the mean value of A_i are calculated together with their standard deviations. Table 2 shows the result.

The ranges of the distribution of the attenuation constant, 0.12-0.19, 0.15-0.23, 0.19-0.26 and 0.23-0.30 $(\text{day})^{-1}$, are the same as the ranges of the linear change for one sunspot cycle. Errors in the estimation of the final level and the attenuation constant are slight, 1.4% at the most, for these ranges of the random distribution of the attenuation

Table 2 Character of the exponential variation, $E(T) = \Delta F - G \exp(-AT)$, approximating to the average of 20 exponential variations, $E_i(T) = -G_i \exp(-A_i T)$, having random distributions of A_i and G_i.
Parameters A and G are estimated by the least square method from the first 5-values of the average of $E_i(T)$, $T = 0, 1, \cdots\cdots, 4$, corresponding to 4Q- or $4Q_a$-case. $\overline{A}_i$ and $\overline{G}_i$ denotes the averages of A_i and G_i, respectively. ΔA and ΔE represent $A - \overline{A}_i$ and $(\sum_{T=0}^{4} (E(T) - \overline{E}_i(T))^2)^{1/2}$, respectively, where $\overline{E}_i(T)$ denotes the average of $E_i(T)$ for $i = 1, 2, \cdots\cdots, 20$. Mean and st. dev. denote the mean and standard deviation, respectively, for 100 different random distributions of A_i and G_i.

A, $(\text{day})^{-1}$ random dis.		$\Delta F/\overline{G}_i$		$\Delta A/\overline{A}_i$		$\Delta E/\overline{G}_i$	
		mean	st.dev.	mean	st.dev.	mean	st.dev.
from	to					$\times 10^{-4}$	$\times 10^{-4}$
0.12	0.19	-0.0136	0.0143	0.0139	0.0246	2.43	1.44
0.15	0.23	-0.0081	0.0111	0.0067	0.0209	2.74	1.76
0.19	0.26	-0.0046	0.0089	0.0038	0.0176	3.16	1.79
0.23	0.30	-0.0031	0.0070	0.0025	0.0153	3.47	1.92
0.12	0.30	-0.0368	0.0145	0.0343	0.0343	3.31	1.43
0.10	0.40	-0.0685	0.0225	0.0656	0.0494	4.10	1.30

constant, though there's a systematic deviation which is negative in the H level or is positive in the attenuation constant. G_i is the deviation of H at $T=0$ from the final level. The time origin, $T=0$, is the day before the first quiet day here. The mean of G_i is less than 50 nT for $4Q_a$-cases of Fig. 2. Then the error in the estimate of the final level of H is not larger than 1 nT, provided that the distributions of G_i and A_i are not so much one-sided. The error of 1 nT must be negligible. As to the attenuation constant also the error of 1.4% is negligible.

When the range of A_i becomes wider, the error increases. For the range from 0.12 to 0.3 $(\text{day})^{-1}$, which is the total range of the linear change shown in fig. 2, the errors are 3.7% for the final level and 3.4% for the attenuation constant as shown in Table 2. The errors of 3.7% and 3.4% are still small, but it may be necessary to note that they are one-side deviations. A wider range of A_i may be expected for the 4Q-cases from 1925 to 1988 discussed in the section 2. If the range is 0.1-0.4 $(\text{day})^{-1}$, the errors are 6.9% and 6.6%. Then the estimated final level should be raised by 2 nT for 29 nT of the mean of G_i in 64 4Q-cases, and the estimated attenuation constant, 0.213, should be lowered to 0.197 in the meaning of the mean of the attenuation constant. These errors are still minor compared with those may come from large noises in H variation.

Estimates of errors are nearly same for different numbers, 10-60, of constituting individual H variation of one average variation as for the number of 20 discussed above.

3.3 Long time variation of the attenuation constant from 1930 to 1983

A remarkable increase of the value of the attenuation constant of the Dst-field is found after 1951. To our regret the stability of the variometer was not enough before 1950's at Kakioka to analyse H variations similarly as the section 3.1. The unstable base line value of the variometer brings much noises in H variation. Use of more numerous cases of H variation must be neccessary to reduce such noises, though the occurrence frequency of $4Q_a$-case is 10.9/year for 1925-1950 which is much higher than 5.8/year for 1951-1981.

The noise reduction is made here by a procedure of two steps of statistics. The first step is the same as the statistics of the section 3.1 except that 11-year average of $4Q_a$-case is used instead of a half cycle. Shifting the beginning of the 11-year period by one year from 1925 to 1978, attenuation constants of the average H variation are obtained for the respective periods. The value of the attenuation constant is considered to be a tentative yearly value of the center year of the 11-year period. The center years are 1930-1983. The tentative yearly values are shown in Fig. 3 by dots. It should be noted that the values in a few years near the time end are not so accurate because of rare occurrence of $4Q_a$-case.

The second step is a smoothing of the tentative yearly values of the attenuation constant. Akaike's Bayesian statistical inference (Akaike, 1980) is an excellent method of smoothing.

Considering a time series of observed values, x_j, it is assumed that the x_j can be decomposed as,

$$x_j = m_j + z_j, \tag{4}$$

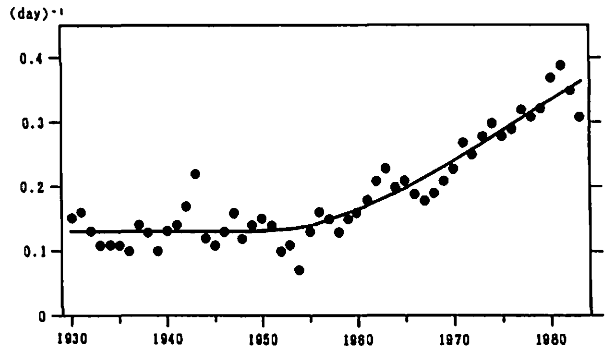

Fig. 3 Attenuation constants of the 11-year average H variation of $4Q_a$-case for 1930-1983. Dots represent the original values of the 11-year average and the line shows their smooth trend calculated by Akaike's Bayesian statistical inference.

where m_j and z_j are trend and random components, respectively. When n observed data, j = 1, ……, n, are given, whole observed values are represented by a vector $\boldsymbol{x}$,

$$\boldsymbol{x}=[x_1, x_2, \cdots\cdots, x_n]^t, \tag{5}$$

where t represents transposition. Similarly the trend component is expressed by a vector $\boldsymbol{m}$,

$$\boldsymbol{m}=[m_1, m_2, \cdots\cdots, m_n]^t, \tag{6}$$

Though many models of $\boldsymbol{m}$ can be considered for the given $\boldsymbol{x}$, the trend $\boldsymbol{m}$ must smoothly vary with time. That means the second-order difference d_j,

$$d_j=(m_j-m_{j-1})-(m_{j-1}-m_{j-2}), j=3,4, \cdots\cdots, n, \tag{7}$$

is nearly zero. Assuming d_j distributes randomly with a variance w, the nearness to zero of d_j is represented by $v \rangle w$, where v is the variance of z_j. Provided c^2 denotes the ratio v/w, c must be larger than 1.

In order to consider the prior distribution of $\boldsymbol{m}$ for the given v and w (or c), a special treatment of m_1, m_2 is necessary, because the second-order differences d_1 and d_2 cannot be determined. Providing $d_1=\alpha m_1$ and $d_2=\beta(m_2-m_1)$, the square sum of d_j is represented by $\|D\boldsymbol{m}\|^2$, where $\|\ \|$ denotes the Euclidean norm and D is given by an $n \times n$ matrix,

$$D=\begin{vmatrix} \alpha & & & & & 0 \\ -\beta & \beta & & & & \\ 1 & -2 & 1 & & & \\ & \cdot & \cdot & \cdot & & \\ & & \cdot & \cdot & \cdot & \\ & & & \cdot & \cdot & \cdot \\ 0 & & & 1 & -2 & 1 \end{vmatrix} \tag{8}$$

If small values are chosen for α and β, particular choice of those values has little influence on model selection.

When observed values $\boldsymbol{x}$ are obtained for the prior distribution of given v and c, the posterior distribution of $\boldsymbol{m}$ is represented by,

$$P(\boldsymbol{m} \mid \boldsymbol{x}) = K \exp\{(-1/2v)(\|\boldsymbol{x}-\boldsymbol{m}\|^2 + \|c D\boldsymbol{m}\|^2)\}, \tag{9}$$

where K is the normalization factor. Minimum of the $\|\boldsymbol{x}-\boldsymbol{m}\|^2 + \|cD\boldsymbol{m}\|^2$ gives the most likely $\boldsymbol{m}$. The $\boldsymbol{m}$ is obtained by solving an extended least square problem,

$$\min_{\boldsymbol{m}} \|\boldsymbol{x}^* - F^*\boldsymbol{m}\|^2, \tag{10}$$

where $\boldsymbol{x}^*$ is a $2n$-component vector $[x_1, x_2, \cdots\cdots, n, 0, 0, \cdots, 0]'$ and F^* is a $n\times 2n$ matrix,

$$F = \begin{bmatrix} I_{n\times n} \\ \\ cD \end{bmatrix} \tag{11}$$

$I_{n\times n}$ denotes a $n\times n$ unit matrix.

If c is given, thus we can get the smooth trend $\boldsymbol{m}$. But the value of c is generally not known beforehand. Akaike has introduced a Bayesian information criterion, ABIC,

$$\mathrm{ABIC} = n \log(2\pi) + n \log v - n \log c^2 - 2 \log|D| + \log|F^{*\prime}F^*| + s^2/v \tag{12}$$

to obtain the value of c from the observed values $\boldsymbol{x}$, where $|\ |$ denotes the determinant and $s = \|\boldsymbol{x}^* - F\boldsymbol{m}^*\|$. At the minimum of ABIC the distribution of $\boldsymbol{m}$ is most likely. The minimum with respect to v occurs at $v = s^2/n$. Replacing v by s^2/n,

$$\mathrm{ABIC} = n \log s^2 - n \log c^2 - 2 \log|D| + \log|F^{*\prime}F^*| + const. \tag{13}$$

The *const* is a constant independent of maximization of likelihood. Using the value c which makes ABIC minimum, (10) gives the smooth trend $\boldsymbol{m}$.

Applying Akaike's Bayesian inference to the smoothing of the yearly tentative values of the attenuation constant, the minimum of ABIC occurs at $c=27$. The smooth trend of the yearly values is calculated by (10), and shown by the smooth curve of Fig. 3.

Looking at the smooth trend of the attenuation constant, a character of nearly constant before 1950's is conspicuous compared with the linear increase after the middle of 1950's. Reason why the increase begins at that time is not known. A magnetospheric pollution due to human activity might be one of the reason.

4. Estimate of the zero level of Dst, Dst0

An estimate of Dst0, that is H-value at Dst=0, is given by the final level of the average H variation of $4Q_a$-case. The analysis of the previous section may give the estimate together with the value of the attenuation constant. However the estimate of the final level is affected much by the estimated value of the attenuation constant. An error of the estimated attenuation constant enlarges the error of the final level of H. Applying here the smoothed attenuation constant obtained in the previous section to the approximation for the average H variation of the 11-year period same as that in the previous section, a more accurate final level of H is obtained.

In this calculation H values of each individual $4Q_a$-case are represented by deviations from the quiet day yearly mean value of H, QDYM, with a correction of the secular change between the day of $4Q_a$-case and the center of the year. It should be noted that QDYM is not the mean of Q_a's but the mean of Q's as reported in the year book of the observatory. A smooth trend of QDYM is substituted for the secular change. The smooth trend consists of 11-year running averages and a correction which is necessary at and near the extreme of the derivative of the 11-year running average. Smoothing of the 11-year running average is not necessary, because the parameter c of the Akaike's Bayesian inference is smaller than 1 if it is applied. But the 11-year running average has a trend which deviates from the original values at the extreme of its derivative. Applying Bayesian inference with an appropriate value of the parameter c, the trend of the difference between the 11-year running average and the original value is calculated (Fig. 4). The value of the parameter c is 16 which is chosen so as to minimize the 11-year period component in the trend and maximize the range of the trend. The smooth trend of the quiet day yearly mean value of H, $(\mathrm{QDYM})_s$, is the sum of the 11-year running average and the trend of difference. The smooth trend is used here for the correction of the secular change in the analysis of H variation to determine the final level.

The determined final levels of H are shown in Fig. 5 by dots. The level of H is Dst0

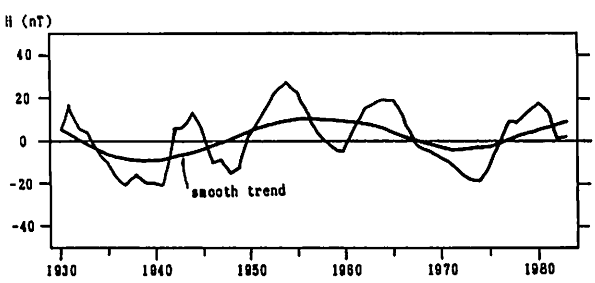

Fig. 4 Deviations of the quiet day yearly mean of H, QDYM, from its 11-year running average and their smooth trend calculated by Bayesian inference with the parameter c =16.

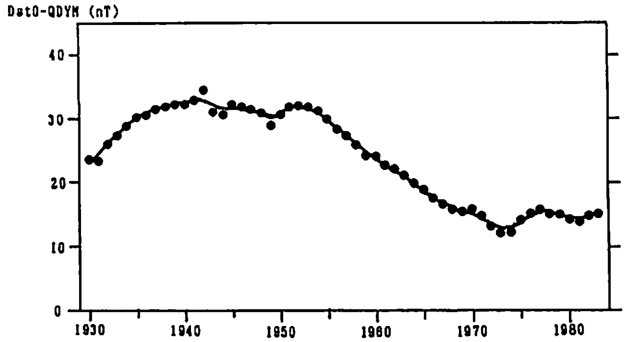

Fig. 5 Long time variation of the final level, Dst0, of the 11-year average of $4Q_a$-case expressed by the deviation from QDYM. Dots represent original values and the line shows their smoothed values, $(\mathrm{Dst0\text{-}QDYM})_s$.

expressed by the deviation from the quiet day yearly mean value, that is Dst0-QDYM. The $(\mathrm{QDYM})_s$ is not chosen as a base of the level, because it is not clear if the smooth trend, $(\mathrm{QDYM})_s$, expresses the secular variation properly or not. Nevertheless the correction of the secular change using the $(\mathrm{QDYM})_s$ has little influence on the result of H final level calculation, because it works only for an uneven distribution of $4Q_a$-case in a year.

The H levels shown by dots of Fig. 5 are again smoothed by Akaike's Bayesian inference. The value of parameter c minimizing ABIC is 1.3. The result is $(\mathrm{Dst0\text{-}QDYM})_s$ shown by the smooth curve of Fig. 5. A long time variation is noticeable in the figure.

4.1 Long time variation of the quiet day mean of H

The long time variation of $(\mathrm{Dst0\text{-}QDYM})_s$ of Fig. 5 does not mean a variation of Dst0. Its main part may be a variation of QDYM because quiet days occur in the course of H-recovery after a disturbance with an H-decrease. H-values of the quiet days depend on the intensity of the preceding disturbance, the attenuation constant and the time interval between the quiet day and the preceding disturbance. The attenuation constant shows a remarkable long time variation (Fig. 3) which is nearly antiproportional to the variation of Fig. 5. If the intensity of the disturbance field and the time from the disturbance to the quiet day are constant throughout the data period, the change of QDYM has to be proportional to $-\exp(-A)$, where A denotes the changing attenuation constant. Actually the correlation between $(\mathrm{Dst0\text{-}QDYM})_s$ and $\exp(-A)$ is 0.9. That explains the most part of the variation of $(\mathrm{Dst0\text{-}QDYM})_s$. Nevertheless the residual still shows a large long time variation whose range is about 12 nT. A possible cause may come from a change of the intensity of the disturbance field.

The intensity of the disturbance field may vary with the solar activity even in the meaning of the sunspot cycle average. Fig. 6 shows the 11-year running averages of the yearly mean sunspot number, $(\mathrm{SPYM})_s$, and of the difference between the quiet day yearly mean and the all day yearly mean of H, $(\mathrm{QDYM\text{-}ADYM})_s$. Here $(\quad)_s$ denotes the smoothed one, but the smoothing is made only by the 11-year running avarage because the second step of Akaike's Bayesian inference has no meaning for $c<1$. Looking at the figure it is easily known that the two curves are nearly parallel. Its correlation coefficient is 0.856. The main part of $(\mathrm{QDYM\text{-}ADYM})_s$ can be explained by the change of the solar activity.

Then linear regression equations of two variables, $\exp(-A)$ and $(\mathrm{SPYM})_s$, are applyed to $(\mathrm{Dst0\text{-}QDYM})_s$ and $(\mathrm{QDYM\text{-}ADYM})_s$. The correlation coefficient of $(\mathrm{Dst0\text{-}QDYM})_s$ increases from 0.9 to 0.914 and that of $(\mathrm{QDYM\text{-}ADYM})_s$ increases from 0.856 to 0.883. Both increases are significant judging from Akaike information criterion, AIC, though the amounts of the increase are rather slight. Excluding the two components depending on $\exp(-A)$ and $(\mathrm{SPYM})_s$, the residual parts of $(\mathrm{Dst0\text{-}QDYM})_s$ and $(\mathrm{QDYM\text{-}ADYM})_s$ are shown in Fig. 7. The residual of $(\mathrm{Dst0\text{-}QDYM})_s$ shows still a remarkable long time variation, compared with a vague or slight variation of the residual of $(\mathrm{QDYM\text{-}ADYM})_s$.

The residual variation of $(\mathrm{Dst0\text{-}QDYM})_s$ appears to be a '60-year period variation' (Yokoyama & Yukutake 1991), if we select from the known type of variation. The present

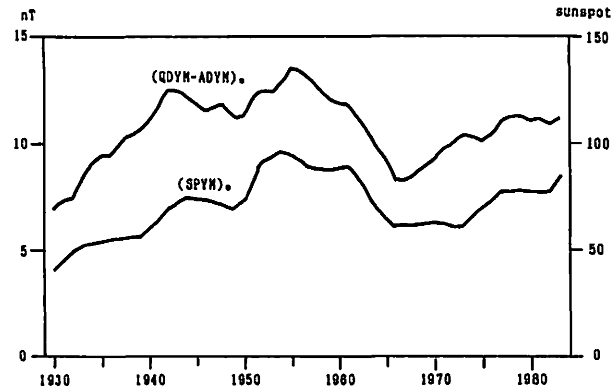

Fig. 6 11-year running averages of the yearly mean sunspot number, $(SPYM)_s$ and those of the difference between the quiet day yearly mean and the all day yearly mean of H, $(QDYM-ADYM)_s$. Close correlation is clear (correlation coefficient = 0.853).

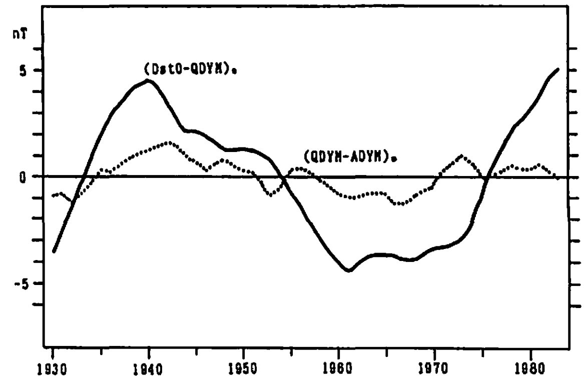

Fig. 7 Residual parts of $(Dst0-QDYM)_s$ and $(QDYM-ADYM)_s$ when the components proportional to exp $(-AT)$ and $(SPYM)_s$ are excluded. A "60-year period variation" is clear for $(Dst0-QDYM)_s$, but not clear or slight for $(QDYM-ADYM)_s$.

60-year period variation is not a variation of the field of the earth interior because a variation of the internal earth field has to be included equally in the both of Dst0 and QDYM. And the variation is not a variation reflecting a change of the disturbance field intensity because the residual of $(QDYM-ADYM)_s$ does not show such a variation clearly. The cause of the variation is not clear. A candidate of the cause might be an existence of the post perturbation which is noted in the old data (Chapman and Bartels, 1940) as a very slowly changing field. On the recent magnetogram it is difficult to notice the perturbation clearly, though the increased magnetic activity (Yanagihara, 1991) may obscure the slowly changing variation.

4.2 Solar cycle dependence of Dst0

The occurrence frequency of the $4Q_a$-case is not enough to obtain a year-to-year change of Dst0, but it may be possible to obtain the mean Dst0 for a half solar cycle. Applying the smoothed value of the attenuation constant to the approximation of the average variations of $4Q_a$-case in the sunspot active years (>80) and the calm years (<80), Dst0-QDYM is calculated. The analysis of the previous section shows Dst0-QDYM has a long time variation expressed by $(\mathrm{Dst0\text{-}QDYM})_s$. In order to know the solar cycle dependency, Dst0-QDYM-$(\mathrm{Dst0\text{-}QDYM})_s$ is calculated. The result is shown in Fig. 8 together with the averages of the sunspot number, $(\mathrm{QDYM})_s$-QDYM and QDYM-ADYM for the same period, where $(\mathrm{QDYM})_s$ means the smooth trend of QDYM described in the section 4.

The variation of Dst0-QDYM-$(\mathrm{Dst0\text{-}QDYM})_s$ is nearly propotional to the sunspot number and nearly same as that of $(\mathrm{QDYM})_s$-QDYM for the first two cycles, suggesting that the Dst0 does not depend on the solar activity though the amplitude of Dst0-QDYM-$(\mathrm{Dst0\text{-}QDYM})_s$ is slightly smaller than that of $(\mathrm{QDYM})_s$-QDYM. After the first two cycles this character disappears gradually. Even for the QDYM-ADYM the solar cycle dependence becomes vague in the last two cycles. One possible reason of the vague relation might be an effect of the solar wind compression.

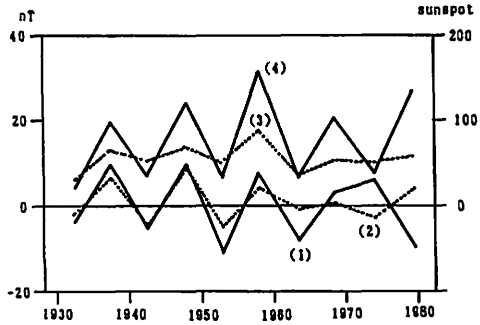

Fig. 8 Solar cycle dependences of (1) $(\mathrm{QDYM})_s$-QDYM, (2) Dst0-QDYM-$(\mathrm{Dst0\text{-}QDYM})_s$, (3) QDYM-ADYM and (4) the sunspot number represented by their averages for active years (sunspot number >80) and those for calm years (<80).

5. Concluding remark

Desire to know the disturbance-free field leads us to analyse H variations on quiet days occurring successively. The H variation is exponential with an attenuation constant, reflecting the decay of equatorial ring currents produced in the preceding disturbance. Present analysis gives the estimates of the attenuation constant and the final level of H which means the base line of Dst. The attenuation constant shows a long time variation, influencing the quiet day mean value of H. Excluding the effect of the change of the attenuation constant and that of the sunspot activity from the quiet day mean value of H, the residual shows a '60-year period variation' with a range of 10 nT. These newly found long time variations are interesting, but their causes remain to be investigated.

Another way of the analysis is the separation of the internal and external parts of the geomagnetic field by the spherical harmonic analysis for widely distributed data, giving solar cycle variations of the external parts (Yukutake & Cain, 1979, 1987). But the accuracy of the observed data, particularly that of the vertical component Z, may limits preciseness of the results.

The present analysis also includes errors due to noises such as the day-to-day changes of the diurnal variation, minor distubances, solar wind compression and the base line value of the variometer. Nevertheless the statistical noise reduction works effectively for obtaining the long time variation. An information of solar cycle variations also can be obtained by the average for a half cycle. The attenuation constant is not depending on the sunspot activity in a solar cycle. The quiet day yearly mean of H shows a rather large solar cycle variation, that is the same as the result of the external part analysis by Yukutake and Cain. But the solar cycle variation becomes vague in the recent cycles.

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柿岡の地磁気水平成分変化から推定したDstのゼロレベルと減衰係数の長期変動

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概 要

擾乱の後の静穏期は長く続かず次の擾乱が起こってしまうので，Dstがゼロである状態はなかなか分かりにくい．いわゆる静穏日は擾乱のDstが減衰する過程で起こりその時の地磁気水平成分HはDstゼロの状態よりかなり小さいと考えられる．事実，静穏日が連続して起きているときのHの経日変化は指数関数的上昇で，その最終到達レベルはかなり大きな値と思われる．このことはまた静穏日のH経日変化を解析することによってDstゼロのHのレベルを求めることができることを意味する．しかし様々な雑音，例えば日変化および太陽風圧縮の日日変化，微小な擾乱あるいは変化計の基線値の安定性等々，のため単一のH変化を解析してDstゼロのレベルを求めることは困難である．統計的手段に頼らざるをえない．静穏日を統一した基準によって新たに選択し，この静穏日が4日連続して起きている場合を重ね合わせ平均のH変化を基礎資料とした．このH変化が指数関数で表せることは明かであるのでこれを解析して減衰係数と最終到達レベルを求めた．

減衰係数については太陽活動周期に依存しないこと，1950年代以前はほぼ一定であったが以後急激にまた一様に増大していることなどが分かった．DstゼロのHレベルは静穏日平均より10ないし30nTくらい大きい．この差は静穏日のDstがまだゼロに到達していないためのものであるが，20nT程度の大きな長期変動を示す．これはDstゼロレベルの変動ではなくてむしろ静穏日平均値の変動を示すものであろう．この長期変動には，減衰係数の変動に起因するものと擾乱の強さの変動に起因するものが含まれるが，その分を取り除いた後にいわゆる60年周期変化と思われるものが10nT程度残る．この60年周期変化は減衰係数の長期変動とともに興味深いが原因が確定できない．今後の問題である．