Memoirs of the Kakioka Magnetic Observatory Vol. 21 No. 1 1984

# Secular and Solar Cycle Variations of Geomagnetic Storm Occurrences at Kakioka

by

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**Abstract**

Various occurrence features of geomagnetic storms during the period from 1924 to 1982 at Kakioka have been investigated in detail relating to sunspot activity. The present study aims mainly to clarify solar cycle and/or heliomagnetic polarity dependences of the storm occurrence frequency. Of course, their secular variation are also a very interesting subject. Main results are as follows;

(1) Annual sc-storm occurrence frequency as a function of the sunspot number has such a heliomagnetic polarity asymmetry as the larger (smaller) storms occur more frequently in the S (N) polarity epoch of the heliomagnetic field. In particular the huge storms (sc-amplitude>100 nT or storm range>500 nT) occur only in the S polarity epoch.

(2) Annual sc-storm occurrence frequency has a good correlation with the sunspot number as high as 0.9, except in the present 21st solar cycle.

(3) Sg-storm occurrence frequency has a major and a minor maximum in the late decreasing and in the increasing phase of the solar cycle, respectively, and shows about one-year difference in the maximum occurrence year between the two heliomagnetic polarity epochs.

(4) Maximum sg-storm occurrence frequency in each solar cycle shows in general such a secular variation (long-term trend) as it changes nearly proportionally to that of the sunspot number, but it is relatively large in the 18th solar cycle and extremely small in the 19th solar cycle.

(5) Sc* occurrence frequency and its occurrence rate against sc's suddenly increased in 1956, and thereafter both have maintained higher values than before on the average.

## 1. Introduction

General occurrence characteristics of the geomagnetic storm have been well studied for a long time relating to solar phenomena such as the sunspot and the solar flare. Therefore, it is one of the most well-known facts that sc-storm (suddenly commenced storm) occurrences mainly caused by the solar flare are closely related to the sunspot activity. And it is also well-known that sg-storm (gradually commenced storm) occur most frequently in the late decreasing sunspot phase of the solar cycle. However, there still remain many problems to be solved on their detailed occurrence features and relationships to the solar phenomena.

Many interesting occurrence characteristics of the sc- and sg-storms at Kakioka were reported by Yokouchi (1953) based on the analysis of the data during the period from 1924 to 1951. Yanagihara (1967) found out that the huge storms at Kakioka have a tendency to occur within a restricted period of alternate solar cycles, roughly speaking, with a 22-year recurrence. Nagai (1977) reported a short note on the relationship between the annual occurrence frequencies of sc- and sg-storms at Kakioka and the sunspot number during the period from 1924 to 1976. The present authors (1982) have analyzed in detail secular, seasonal and diurnal variations in the sc- and sg-storm occurrences and their solar cycle dependences at Kakioka for the two separated periods from 1924 to 1951 (the same as the Yokouchi's) and from 1958 to 1981, and found out many interesting differences in occurrence characteristics for different periods.

Recently, the concept of structure and time behavior of the heliomagnetic field and the heliomagnetosphere has been established by a series of Saito's and Saito et al.'s active studies (Saito 1975, 1979 and Saito et al. 1976, 1980). The so-called two-hemisphere model of the heliomagnetosphere has been proposed, and such dramatic time behaviors as the polarity of the heliomagnetic dipole field is reversed around every maximum sunspot phase and the so-called heliomagnetic excursion takes place in every decreasing sunspot phase have been clarified by the studies. Furthermore, many occurrence characteristics of the geomagnetic storms, in particular, 27-day recurrent geomagnetic disturbances such as the sg-storm could be fairly well explained by the two-hemisphere model and its solar cycle behaviors. In addition to these facts, the structure and time behavior of the M-region or the coronal hole, which is regarded as an origin of sg-storm or 27-day recurrent disturbances, have been clarified based on the two-hemisphere model by Saito (1978) and others.

In this way, the solar phenomena related to the geomagnetic disturbances and their sequence of cause and effect have been rapidly brought to light. Under such situation, it is very interesting to investigate detailed occurrence characteristics of the geomagnetic disturbances relating to the solar cycle variation of the heliomagnetic field. The present authors have tried to investigate various occurrence characteristics of the geomagnetic storms for the 58-year data from 1924 to 1982. The present study is mainly based on various correlation analyses between the geomagnetic storm occurrence frequency and the sunspot number.

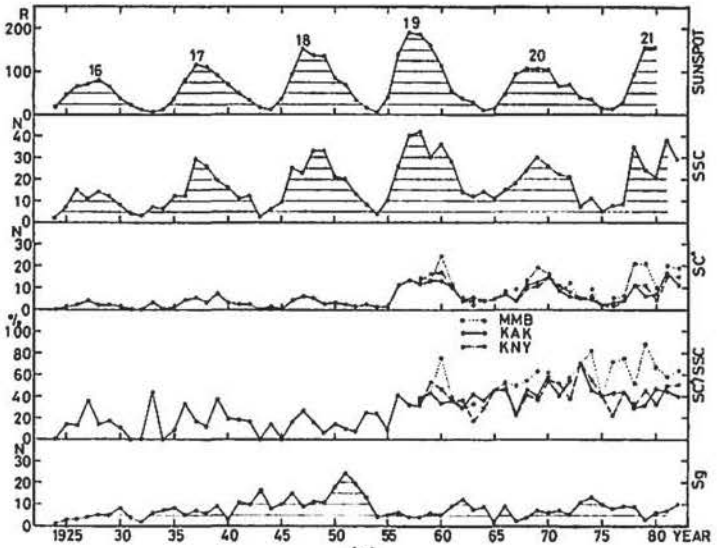
## 2. Geomagnetic storm and sunspot data used in the present study

Geomagnetic storm data used in the present study are mainly from the geomagnetic storm list at Kakioka reported by Yokouchi (1953) for the period from 1924 to 1951 and his continued list for the period from 1952 to 1957 (not published), and from the annual lists for the period from 1958 to 1982 reported by the Kakioka Magnetic Observatory in its year books (Peport of the Geomagnetic and Geoelectric Observations (Rapid Variations) ). The latter data have been reported since the IGY period as the routine work of the Observatory. By the way, as observers or investigators of the geomagnetic storms have been changed many times hitherto, the above geomagnetic storm data were not always made with a constant observational basis. The data during the periods from 1952 to 1957 and from 1973 to 1981 are checked and a little modified by the present authors with a constant observational basis. Because these two periods are fairly unusual in occurrence of the geomagnetic storms comparing with the other periods. Since 1958 the geomagnetic storm data at Memambetsu and Kanoya are referred. On the other hand, in several years before 1924 some partial data from the year books and from some personal reports are also referred.

There are some cases in which two sc's are defined against one storm and a new storm occurs before the preceding storm does not end. In the latter case the storm range of the preceding storm usually is not given. Therefore, the total number of sc's is larger than that of the storm range data. The sunspot number (Zurich relative sunspot number) is only used as the representative solar data related to the geomagnetic storm occurrence in the present study.

## 3. Secular variations of sc- and sg-storm occurrence frequencies and their correlations with the sunspot number

In this section annual occurrence features of various geomagnetic storms at Kakioka (KAK) for the period from 1924 to 1981, partly including those at Memambetsu (MMB) and Kanoya (KNY) since 1958, are summarized and discussed in detail with relation to the annual mean sunspot number. Annual occurrence frequencies of sc-, sc*- (sc with a reverse pre-impulse) and sg-storms during the period present concerned are illustrated together with the sunspot number in Fig. 1. From the top are shown the annual mean sunspot number (SUNSPOT), the annual occurrence frequencies of sc (SSC) and sc* (SC*), the occurrence frequency percentage of sc*'s against sc's (SC*/SSC) and the annual occurrence frequency of sg (Sg), respectively. The sc* data are illustrated together distinguished by the three observatories, KAK, MMB and KNY, because the sc* occurrence shows essentially some latitudinal and longitudinal dependences as well-known. The occurrence frequencies of sc- and sg-storms since 1958 are represented by mean values of the three observatories, and all of them shown are of a simple annual summation of storm occurrence times without any dis-



(a)

Fig. 1. Annual occurrence frequencies of the geomagnetic storms (sc-, sc*- and sg-storms) at Kakioka (partly including Memambetsu and Kanoya) and the annual mean sunspot number.

tinction of the storm magnitude (Quality), this kind of occurrence frequency being named as 'simple occurrence frequency'. The numerals shown in the panel of the sunspot number are the solar cycle number.

3.1 General relationship between the geomagnetic storm occurrence and the sunspot number

(a) Sc-storm

As can be clearly seen in Fig. 1, the secular variation curve of the sc-storm occurrence frequency changes well parallelly with that of the sunspot number. Of course, it has been well known in general from old times that the above feature is one of the most definite characteristics in geomagnetic disturbance. However, such a study as the present one using a long period data has not been carried out hitherto. Then, more detailed occurrence characteristics can be analyzed in the present study and many interesting results will be presented herein.

For a more reasonable analysis, in addition to the simple occurrence frequency shown in Fig. 1, a weighted one should be taken into consideration. This weighted occurrence frequency is a sum of the storm occurrence times with a following weight according to the magnitude of sc-amplitude or storm range (in H-component in both cases). The sc-amplitude and storm range at Kakioka are grouped into 6 and 7 classes, respectively as shown in Table 1. As a weight in the weighted occurrence frequency, the class number is adopted here. Thus four kinds of storm occurrence frequencies which are of the respective simple and weighted ones for the sc-amplitude and storm

Table 1. Classification of the sc-amplitude and the storm range for estimation of the weighted occurrence frequency.

| Class No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Sc Range (nT) | <20 | 20–39 | 40–59 | 69–79 | 80–99 | >100 | |
| Storm range Range (nT) | <100 | 100–199 | 200–299 | 300–399 | 400–499 | 500–599 | >600 |

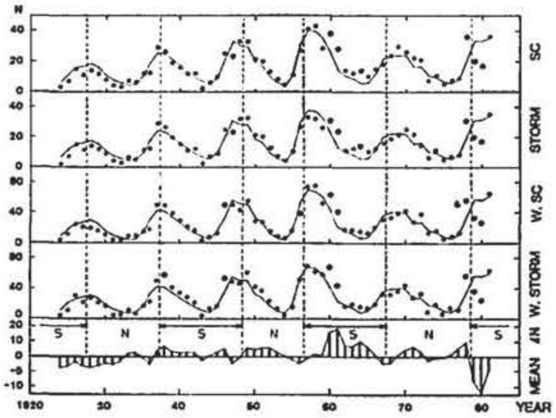


Fig. 2. Annual simple (weightless) and weighted occurrence frequencies of the sc-storms for the sc-amplitude and the storm range (dots), and respective estimated ones (curved lines) obtained from a function of the sunspot number.

range are obtained as illustrated in Fig. 2. The upper two diagrams are of the simple occurrence frequencies of sc-amplitude (SC) and storm range (STORM), and the lower two are of the weighted ones of sc-amplitude (W. SC) and storm range (W. STORM), respectively. Each full line curve is an estimated occurrence frequency obtained from each regression equation against the sunspot number, being exactly equivalent to the variation of sunspot number. Mean $\Delta$N shown at the bottom is mean of deviations of the four actual storm occurrence frequencies from each estimated value (full line). Besides, the storm occurrence frequency data marked by ◉ are of ones much greatly deviated from the estimated value, and the N and S marks indicate the polarity of the heliomagnetic field, the vertical broken line indicating each boundary of two polarity epochs.

As can be found from these figures, all the storm occurrence frequencies have on the whole a high positive correlation with the sunspot number as if there is a linear relationship between two variables. Their correlation coefficients, which are obtained by omitting some 10% data marked by ⊙ in Fig. 2, amount to about 0.95 in every case. In general, such a correlation coefficient for the weighted occurrence frequency ($\gamma=0.96$) is slightly larger than that for the simple one ($\gamma=0.94$) in both cases of sc and storm range. Though their differences are quite small, the above characteristics seem to somewhat reflect a reasonable feature that the larger storms more frequently occur as the sunspot number becomes greater. This will be again discussed in the next subsection. As for detailed features, some systematic differences from the general relationship can be found. This will suggest different characteristics in the relationship between the storm occurrence and the sunspot number for different solar cycles and different solar phases. This matter will be also again dicussed in the next subsection.

In this way, the general secular variation of the sc-storm occurrence frequency is closely related to that of the sunspot number. This is really a natural result, because almost all of the sc-storms are caused by a corpuscular stream which is emitted more frequently and more strongly according to an increase of the solar activity (the sunspot number). However, it should be noted that in the present maximum sunspot phase (in the 21st solar cycle) this relationship is fairly broken as shown in the correlation coefficients for each solar cycle given in Table 2. This is the most incomprehensive feature with regard to the sc-storm occurrence during the present analyzed period. Furthermore, it should be pointed out as another strange feature that the sc-storm occurrence frequency in the minimum sunspot phase of the 19th solar cycle is extremely higher than those of the other solar cycles.

(b) Sc*-storm

As for sc* occurrence feature, the sc* occurrence frequency is roughly proportional to that of the sc-storm as can be seen in Fig. 1. Of course, a positive correlation

Table 2. Correlation and regression coefficients between the sc-storm occurrence frequency and the sunspot number for the 16th to 21st solar cycles.

| | | SC | | | STORM | | |
|---|---|---|---|---|---|---|---|
| Cycle NO. | Period | r | a | $a_0$ | r | a | $a_0$ |
| 16 | 1924-33 | 0.887 | 0.155 | 2.2 | 0.900 | 0.156 | 1.9 |
| 17 | 1933-44 | 0.920 | 0.186 | 3.9 | 0.931 | 0.192 | 3.3 |
| 18 | 1944-54 | 0.940 | 0.171 | 6.4 | 0.933 | 0.178 | 5.5 |
| 19 | 1954-64 | 0.879 | 0.161 | 9.5 | 0.896 | 0.129 | 9.4 |
| 20 | 1964-76 | 0.965 | 0.181 | 6.1 | 0.897 | 0.139 | 6.7 |
| 21 | 1972-81 | 0.696 | 0.136 | 6.7 | 0.707 | 0.125 | 5.8 |
| | | W. SC | | | W. STORM | | |
| 16 | 1924-33 | 0.877 | 0.469 | 2.1 | 0.873 | 0.372 | 2.4 |
| 17 | 1933-44 | 0.937 | 0.628 | 4.8 | 0.917 | 0.513 | 4.7 |
| 18 | 1944-54 | 0.951 | 0.532 | 6.7 | 0.905 | 0.411 | 10.6 |
| 19 | 1954-64 | 0.909 | 0.531 | 14.8 | 0.919 | 0.420 | 11.2 |
| 20 | 1964-76 | 0.919 | 0.496 | 11.3 | 0.913 | 0.355 | 8.0 |
| 21 | 1972-81 | 0.705 | 0.408 | 15.4 | 0.632 | 0.244 | 13.1 |

with the sunspot number can be found similarly to the case of sc-storm through the whole period and at the three observatories.

However, it is very strange and noteworthy that the sc* occurrences at Kakioka suddenly increased in 1956 and became on the average much more frequent thereafter. Simultaneously, the ratio of SC*/SSC also suddenly increased in 1956 and was also kept on the average higher than before with showing a slight increasing trend, especially at Memambetsu.

By the way, these features might be closely related to the sensitivity and resolution of the geomagnetic observation which changed greatly from epoch to epoch. The magnetograph at Kakioka has been improved several times hitherto. Consequently, it is difficult to regard all the above-mentioned matters as a natural features. However, since the regular recording apparatus was not changed around 1956, at least, the sudden increase of the sc* occurrence frequency in 1956 is regarded as a natural feature. This feature is one of the most incomprehensive secular variations of the sc* occurrence frequency. Its reason cannot be well explained, but it is not doubtful that a nature of the solar wind (corpuscular stream) changed greatly around 1956, as if its causation seemed to be related to the beginning of the greatest sunspot activity in the 19th solar cycle in this century.

As for the solar cycle dependence in the variation of ratio of SC*/SSC (occurrence rate of sc*), the ratio changes so irregularly and greatly from year to year that it is difficult to find clearly its distinct feature. As a whole, however, the ratio seems to become large with the increase of the sunspot number as well as the sc* occurrence frequency itself, at least, in the former half period (before 1955).

(c) Sg-storm

As for the sg-storm occurrence, it is also very interesting to note that following strange features in its secular variation are found in Fig. 1. Namely, the annual sg-storm occurrence frequency gradually increased in general tendency until about 1953, suddenly decreased in the next year and thereafter showed again a slight increasing tendency with a short-term variation which is related to a solar cycle variation. In particular, it is notable that sg-storms occurred extremely frequently around 1951 in the 18th solar cycle. From these secular variations it is suggested that a solar state related to the sg-storm origin such as the M-region or the coronal hole changed suddenly aronnd 1954. This change would be closely related to the following great sunspot activity which accompanied the extremely great solar flare activity. And, this solar flare activity and associated high speed corpuscular streams disturbed and modified strongly the steady heliomagnetic field and corpuscular streams which might produce sg-storms. This may result that the sg-storm occurrence frequency in the 19th solar cycle became relatively small. Furthermore, the above-inferred change of the solar state might have some relationship with the sudden increase of the sc* occurrence frequency in 1956.

While, it is well known that sg-storms occur most frequently in the late decreasing sunspot phase. This feature is quite different from the case of sc-storm. Actually, the sg-storm occurrence frequency presented in Fig. 1 has a maximum in a few years before the minimum sunspot phase in every solar cycle. Consequently, a direct correlation between the sg-storm occurrence frequency and the sunspot number would be so low that there seems to be no in-phase relationship between them. If, however, the phase of the sunspot number variation is advanced by two years, their correlation becomes higher, its coefficient amounting to about $-0.6 \sim -0.7$ (cf. $+0.9$ in the case of sc-storm). This will be again in detail discussed in the later section.

It is believed in general that sg-storms are produced by the corpuscular stream emitted continuously from the solar M-region or the coronal hole. The solar cycle dependence of the sg-storm occurrence may be understood as the following. Since the corcpuscular stream of the sg-storm origin emitted from the M-region is disturbed and modified by other sporadic emissions of the strong solar corpuscular stream associated with solar flares, the former stream may not be able to exist stably and steadily in the active sun epoch. On the other hand, during the quiet sun epoch the M-region and accompanying corpuscular stream exist steadily and sg-storm are produced frequently in the late decreasing sunspot phase with a fairly exact 27-day recurrence tendency. The latter fact is related to another condition of the so-called heliomagnetic excursion. In any case, we may consider that stable and long-lived M-regions existed most predominantly in the 18th solar cycle.

Judging from the increasing tendency of the sg-storm occurrence frequency during the former half period (the 16th to 18th solar cycles), it seems to be inferred that the activity of the M-region depends somewhat upon the sunspot activity. This dependence was well kept until the 18th solar cycle, but it was broken at the 19th solar cycle possibly by the extremely great sunspot activity and the associated solar flare activity. In fact, the occurrence number of the solar flare in the maximum sunspot phase of the 19th solar cycle attained to about 600, but those of the other solar cycles (the 20th and 21st cycles) were as quite small as 100 or less. A similar new dependence seems to have reappeared since the 20th solar cycle, though it is not so clear that the revived dependence cannot be clearly verified at presnt for such a short period as about 1.5 solar cycles.

### 3.2 Solar cycle dependence of the geomagnetic storm occurrence in statistical feature

#### (a) Sc-storm

In the previous discussion (in 3.1 subsection) there seemed to be some different features in the relationship between the sc-storm occurrence frequency and the sunspot

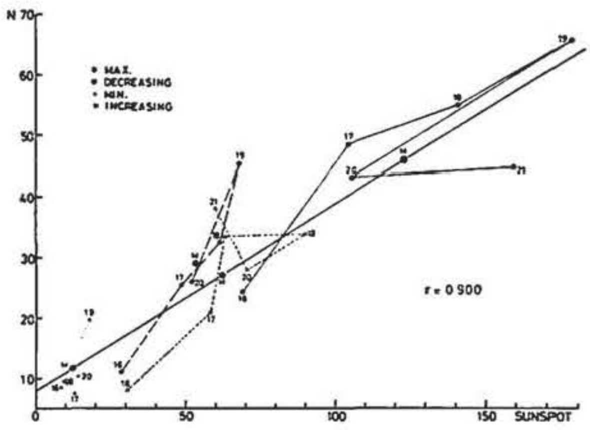



Fig. 3. Correlation scatter diagram between the mean sc-storm occurrence frequency and the corresponding mean sunspot number for four sunspot phases of the solar cycle, shown by the different symbols as remarked.

number for different solar cycles and for different sunspot phases such as maximum, minimum, increasing and decreasing phases. Fig. 3 shows four correlation scatter diagrams between the two variables for these sunspot phases. The storm occurrence frequencies shown here are annual mean values for the four sunspot phases produced from Fig. 2 by the following way. The mean occurrence frequency is defined by mean of twofold simple occurrence frequencies and onefold weighted ones for the sc-amplitude and the storm range (2·SC+2·STORM+W. SC+W. STORM)/4. Because the weighted occurrence frequency is about two times of the simple one on the average. The sunspot number data are mean values for each phase. The dots marked by the large circle are of the mean values of the whole solar cycles for each phase. The oblique line is the regression line obtained as the mean for the whole phases.

In Fig. 3 we notice that four scatter diagrams show some meaningful different correlations for different phases. In particular, it is very remarkable that the correlation in the decreasing sunspot phase is highest, and its regression coefficient (degree of dependence of the sc-storm occurrence on the sunspot number) is also larger than those for the other phases except the minimum phase as given in Table 3. It is also notable that the regression coefficient for the maximum sunspot phase is smallest. In the individual feature the dots for the maximum and increasing sunspot phases of the 21st solar cycle are greatly deviated from each general relationship, showing the strange feature previously mentioned in 3.1 subsection. The regression coefficient for the minimum sunspot phase is largest in appearance, but its confidence is relatively low, because it is mainly effected by an exceptionally high occurrence frequency in the 19th solar cycle. Consequently, this may not be so meaningful as to be regarded as

Table 3. Correlation and regression coefficients between the mean sc-storm occurrence frequency and the corresponding mean sunspot number for four sunspot phases. The values in [ ] are for the data excluding the 21st solar cycle's.

| Sunspot phase | r | a | $a_0$ |
|---|---|---|---|
| Maximum | 0.847<br>[0.962] | 0.292<br>[0.360] | 10.2<br>[4.4] |
| Decreasing | 0.967 | 0.796 | −13.1 |
| Minimum | 0.773 | 1.010 | − 1.5 |
| Increasing | 0.756<br>[0.896] | 0.433<br>[0.448] | 0.2<br>[−3.1] |

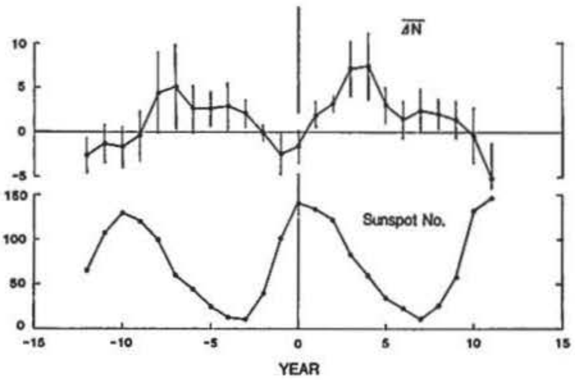



Fig. 4. Mean bei-solar-cycle-period variation of mean deviation of four sc-storm occurrence frequencies from the estimated values for the period of the 17th to 20th solar cycles (top) and corresponding variation of the sunspot number (bottom).

a notable feature. Namely, it is difficult to consider the above regression coefficient as a general sunspot dependence of the sc-storm occurrence in the minimum sunspot phase.

These solar cycle and sunspot phase dependences of the sc-storm occurrence can be also understood by the mean annual deviation of the sc-storm occurrence frequency (MEAN $\Delta$N) presented in Fig. 2. The deviation (hereafter denoted by $\Delta$N) shows in general a positive value in the decreasing sunspot phase and a negative value nearly in the maximum phases. Then, mean variations of $\Delta$N and sunspot number for the 17th to 20th solar cycles are illustrated in Fig. 4. Each vertical bar on dot marks indicates the standard error. As clearly seen in Fig. 4, we can find easily a significant solar cycle variation of $\Delta$N which shows a maximum in the decreasing sunspot phase

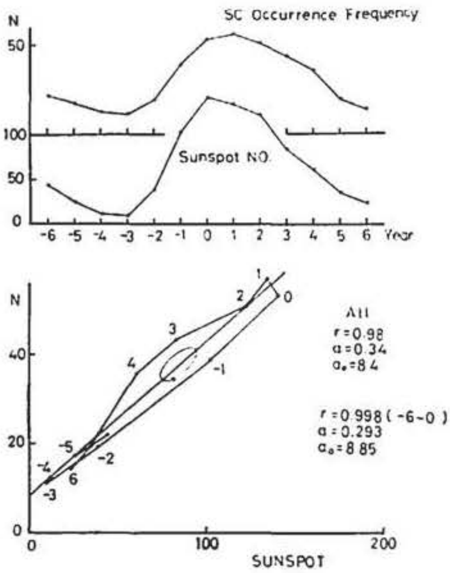



Fig. 5. Mean solar cycle variation of the sc-storm occurrence frequency and its correlation with the sunspot number for the whole solar cycles.

and a minimum in the year just preceding the maximum sunspot phase. This fact seems to mean that the solar flare activity related to the geomagnetic storm has a part following after the sunspot activity a few years. In other words, this may mean that the solar flare activity has an after-effect of the sunspot activity, or that these two activities have some phase-lag in their manner of change.

Furthermore, these characteristics can be confirmed directly from another statistical result as shown in Fig. 5. The upper panel of Fig. 5 is the mean sc-storm occurrence frequency and the mean sunspot number for the 17th to 20th solar cycles (the central year is of the maximum sunspot number and is indicated by 0 year), and the lower panel is their correlation scatter diagram together with some remarks on the correlation and regression coefficients. From this figure it should be first noted that the correlation coefficient becomes as high as 0.98 for such a mean relationship. The solar cycle dependence of the sc-storm occurrence discussed so far is summarized in Fig. 5. Namely, the plotted dots do not distribute at random with respect to the time series, but as the lines connecting between successive-year dots present an elongated counterclockwise loop. This feature is nothing but to mean the after-effect or phase-lag of the solar flare activity against the sunspot activity. Moreover, since the correlation coefficient attains such a high value as 0.998 for the period from $-6$ year to 0 year, it is reasonable to consider that sc-storms occur relatively frequently in the decreasing sunspot phase from 1 year to 4 year due to the after-effect of the sunspot activity.

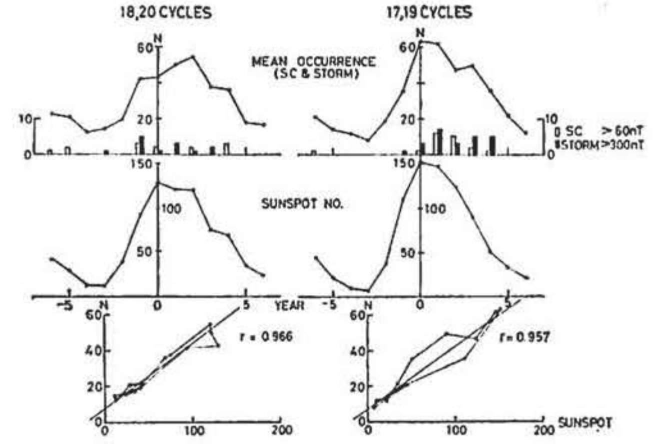



Fig. 6. Mean solar cycle variations of the sc-storm occurrence frequency (top) and their correlations with the sunspot number in the even and odd solar cycles (bottom).

By the way, it would be found from Fig. 1 that the above-mentioned characteristics in the sc-storm occurrence feature are slightly different between the even and odd solar cycles. Then, in Fig. 6 are shown two correlations separated by the even and odd solar cycles with the same manner as Fig. 5. Both the sc-storm occurrence frequency and the sunspot number for the even solar cycle are smaller and more irregular in manner of change than those for the odd solar cycle. Nevertheless, the correlation in the former case is slightly higher than in the latter case as can be seen in the scatter diagram (r: 0.966 vs. 0.957). In the former case a correlation coefficient attains to 0.988, if the data in 0 year is omitted. Thus, it is concluded that the nonlinear relationship between the solar flare and the sunspot activity discussed in Fig. 5 is mainly due to the characteristics in the odd solar cycle, especially in the 19th solar cycle.

(b) Sg-storm

As already mentioned in the previous section, the maximum occurrence frequency of the sg-storm appears in the late decreasing sunspot phase in almost all of the solar cycles. From the same point of view as in the case of sc-storm, mean solar cycle variations of the sg-storm occurrence frequency are presented together with those of the sunspot number in Figs. 7 and 8. In this case the 0 year is taken as the year of the minimum sunspot number. For these statistical analyses four or five solar cycles are adopted, being divided into the even and odd solar cycles, which correspond to the N and S polarity epochs of the heliomagnetic field (refer to Fig. 2 and hereafter the N and S polarity epochs are denoted by N.P. and S.P. epochs). The sg-storm occurrence frequency shown here is a weighted one obtained by the same manner as in the case

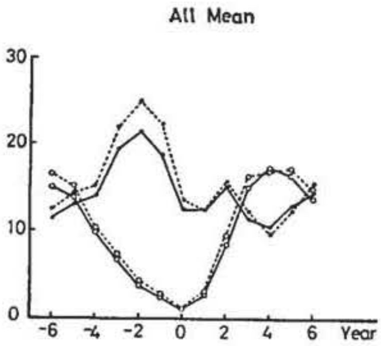



Fig. 7. Mean solar cycle variations of the sg-storm occurrence frequency for the periods from the 16th to 20th solar cycles (full line) and from the 17th to 20th ones (broken line).

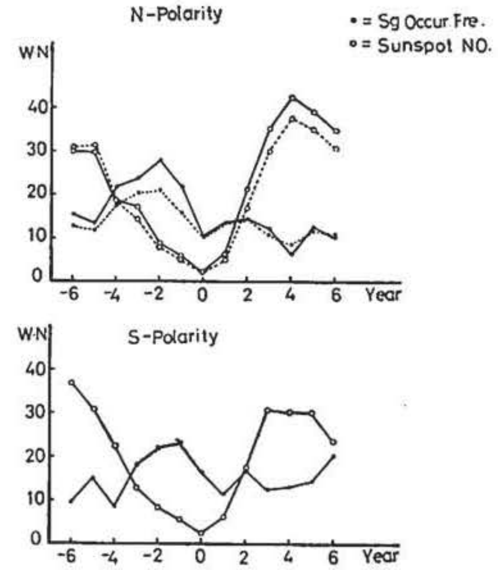



Fig. 8. Mean solar cycle variations of the sg-storm occurrence frequency in the N.P. and S.P. epochs of the heliomagnetic field. The two shown by the broken and full lines in the upper panel are the means for 2 and 3 solar cycles, respectively.

of sc-storm. Fig. 7 shows mean solar cycle variations for the 16th to 20th solar cycles (full line) and the 17th to 20th ones (broken line), and Fig. 8 shows those for the even and odd solar cycles, in other words, the N.P. and S.P. epochs. Two curves are illustrated for the N.P. epoch, being for the three (full line) and the two solar cycles (broken line).

As can be clearly seen in Fig. 7, both mean sg-storm occurrence frequencies show such a typical solar cycle variation as is particularly high during three years of the late decreasing sunspot phase with a clear maximum in $-2$ year (two years before the minimum sunspot year). Furthermore, it is very interesting to note that a secondary maximum of the sg occurrence frequency seems to appear in $+2$ year during the increasing sunspot phase, but it is not certainly known whether the secondary maximum is of a general feature or not. Though there is little difference between the two means of the sunspot number, there is a slight difference in magnitude between the two sg occurrence frequencies, in particular, in the former half period. This is mainly due to the extremely frequent sg occurrence in the 18th solar cycle as presented in Fig. 1.

Meanwhile, the solar cycle variation of the sunspot number shows a clear difference between the even and odd solar cycles or N.P. and S.P. epochs as easily seen in Fig. 8. As if related to this different feature, the year of the major maximum sg occurrence frequency is different by about one year between the two epochs, being about −2.5 year and −1.5 year for the N.P. and S.P. epochs, respectively. And, the secondary sg occurrence peak seems to be more predominant in the N.P. epoch. These characteristics may be related to the previously mentioned difference in the solar cycle variation of the sc-storm occurrence frequency between the even and odd solar cycles. Namely, the more frequent sc-storm occurrence during the late decreasing sunspot phase in the odd solar cycle or in the S.P. epoch may cause the delay of year of the sg maximum occurrence frequency in that period, because of some kind of control effect of the sc-storm (solar flare) on the sg-storm occurrence. Besides, it should be remarked that both variations of the sg occurrence frequency and the sunspot number are rather irregular in the S.P. epoch.

As introduced in section 1, Saito (1976) has found out that sg-storms occur more frequently when some excursions of the heliomagnetic field take place during the decreasing and minimum sunspot phases. In order to clarify the mechanism of sg-storm occurrence, the above behavior of the heliomagnetic field should be taken into consideration in addition to certain control effect of the sc-storm occurrence, that is to say, an effect of the solar flare activity.

## 4. Occurrence distributions of sc-amplitude and storm range

### 4.1 Sc-amplitude and storm range

In this section we discuss some other interesting occurrence features of the sc-storm mainly concerned with their heliomagnetic polarity dependences. In Figs. 9 and 10 are presented annual occurrence distributions of sc-amplitude and storm range together with the sunspot number. The vertical lines are boundary between the N.P. and S.P. epochs, being not so definite. Several dots with numeral symbols should have been plotted outside the figure. The numeral indicates the value of sc-amplitude or storm range. (The data before 1924 do not present all sc-storms). In addition, annual occurrence frequencies based on respective various classes of the sc-amplitude and storm range are illustrated together with the sunspot number in Figs. 11 (sc-amplitude) and 12 (storm range). Details of each classification are indicated in each figure.

From these figures it is easy to find such a well-known common feature as the larger the sunspot number, the larger sc-amplitude or storm range occur more frequently. In addition to this common feature, the most interesting fact is that there is a clear difference in the sc-storm occurrence feature between in the N.P. and S.P. epochs. Namely, both large sc-amplitude and storm range occur more frequently in the S.P. epoch, especially the sc-storms larger than 100 nT in sc-amplitude and 500 nT

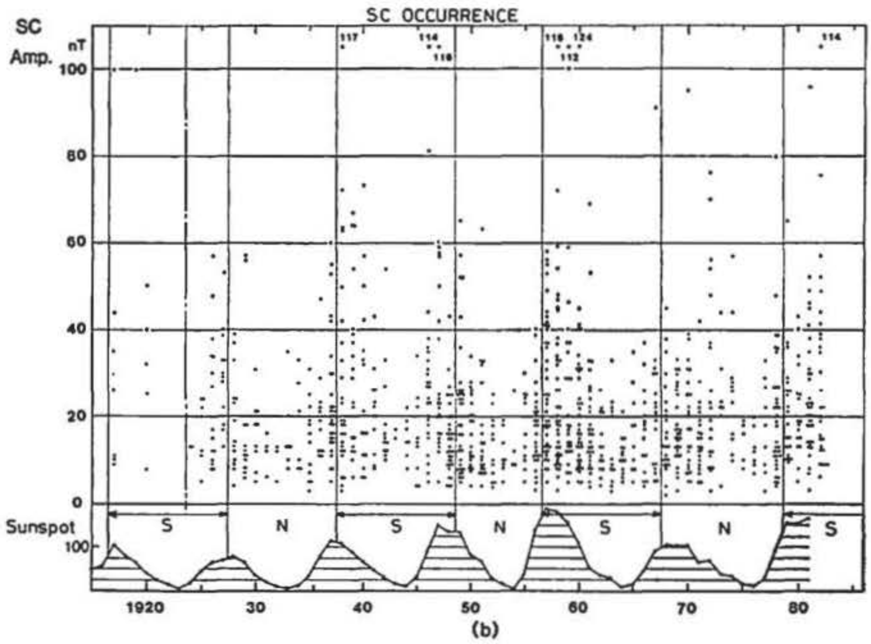



Fig. 9. Annual occurrence distribution of the sc-amplitude. Symbols, N and S indicate the polarity of the heliomagnetic field, the vertical lines are each boundary between the N.P. and S.P. epochs.

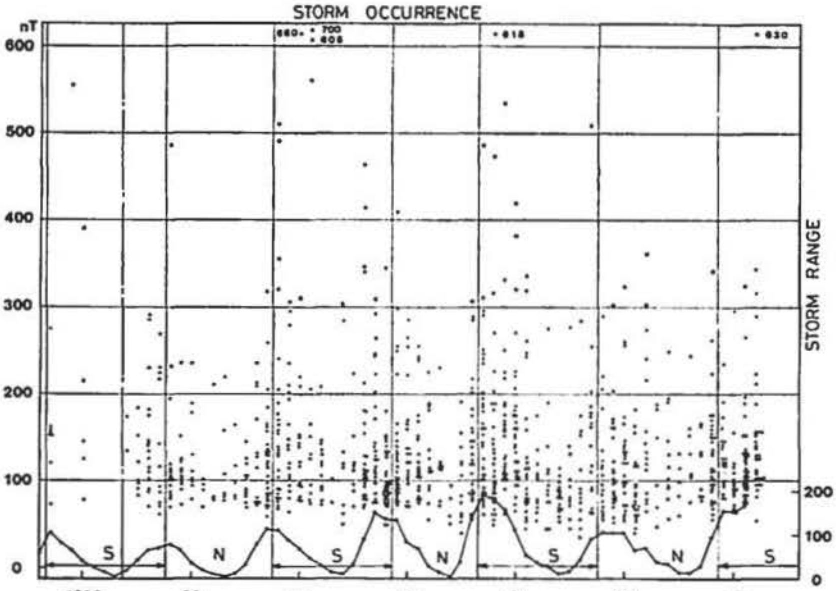



Fig. 10. The same as Fig. 10 except for the storm range.

in the maximum sunspot phase, partly in the decreasing sunspot phase and none of them in the minimum sunspot phase.

In this way, there is a distinct asymmetry of the sc-storm occurrence feature with respect to the heliomagnetic field polarity. Then, Fig. 13 shows distributions of the


Fig. 11. Annual sc-storm occurrence frequencies based on various classes of the sc-amplitude.

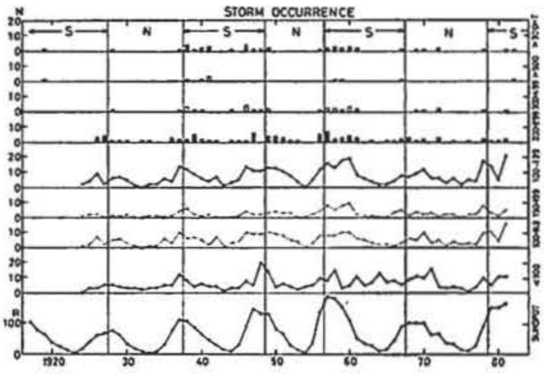



Fig. 12. The same as Fig. 12 except for the storm range.

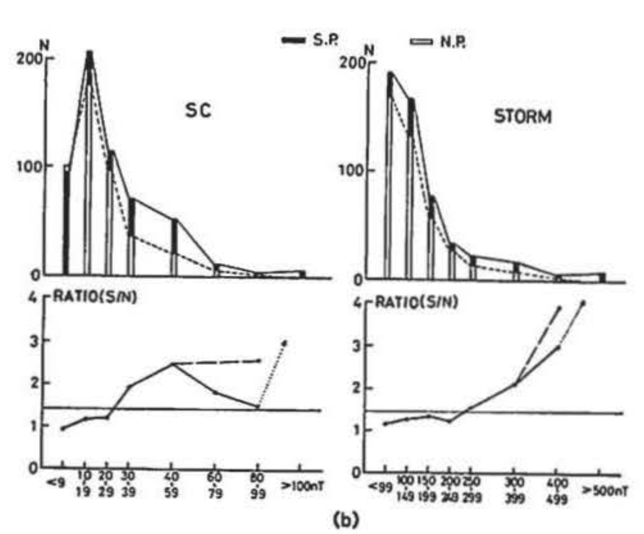



Fig. 13. Occurrence frequency distributions of the sc-amplitude and storm range for the S.P. and N.P. epochs (top), and occurrence frequency ratios (S/N) between the two epochs (bottom).

storm occurrence frequency with respect to the sc-amplitude (SC) and the storm range (STORM) which are classified into 8 classes according to their magnitude (upper) for the S.P. and N.P. epochs, and ratios of the occurrence frequencies in each class between the two epochs (RATIO (S/N)). The total number of years for each epoch is exactly equal to each other, being 29 years. The horizontal line in the lower panel is the ratio of the sunspot number between the two epochs. This ratio is 1.42. Each arrow of the dotted line indicates an infinite value, because of the zero occurrence frequency in the N.P. epoch, and each broken line is for the group of the last three classes.

All storm occurrence frequencies in every class except the first class of SC are larger in the S.P. epoch. As one of its reasons there is a fact that the mean sunspot number is considerably larger in the S.P. epoch as already mentioned. This is regarded as a significant difference of the sunspot activity itself depended upon the polarity of the heliomagnetic field. When the sc-storm occurrence frequencies for the two epochs are exactly compared with each other as a function of the sunspot number, the above difference should be taken into consideration. Consequently, when the S/N ratio of the storm occurrence frequency in each class is larger than about 1.4 (the ratio of the sunspot number) as shown by the horizontal line in Fig. 13, we can say that the sc-storms occur more frequently in the S.P. epoch in feature normalized by the sunspot number. If thus considered, the sc-storm larger than 30 nT in sc-amplitude and 250 nT in storm range occur more frequently and vice versa in the S.P. epoch. And as already pointed out, it is one of the most significant features that the sc-storms larger than 100 nT in sc-amplitude and 500 nT in storm range occur only in the S.P. epoch. This corresponds to a roughly 22-year recurrence of the huge sc-storm occurrence. The above feature is always kept true in the beginning phase of each S.P. epoch for the whole period, but not always in the ending phase. Furthermore, detailed characteristics are different between in the sc-amplitude and the storm range. The largest sc-amplitude occurred in the 19th solar cycle (1960), but the largest storm range in the 17th solar cycle (1941) in spite of the relatively small sunspot number. The solar cycle dependence of the sc-amplitude is as a whole more predominant than that of the storm range. In addition to such features it is very notable as an unusual feature that the sc-amplitudes larger than 40 nT occur most frequently in the decreasing sunspot phase of the 20th solar cycle within the last N.P. epoch. Such feature cannot be seen in the other epochs.

On the other hand, the S/N ratios of the total simple occurrence frequency for the sc-amplitude and the storm range are nearly equal, being about 1.27. The similar ratios of the weighted occurrence frequency are also equal, being about 1.50. The former is less and the latter nearly equal to or a little larger than that of the sunspot number (1.42). This means that the simple sc-storm occurrence frequency normalized by the sunspot number is larger in the N.P. epoch. And, the weighted occurrence frequency is rather well linearly proportional to the sunspot number. This may be a natural result, because the weighted occurrence frequency is a more reasonable measure of the storm activity mainly related to the sunspot activity than the simple one. Besides, it may be a possible explanation for the above-mentioned S/N polarity asymmetry of the sc-storm occurrence that the ratio of the weighted occurrence frequency is a little larger than that of the sunspot number.

The above-discussed features in the sc-storm occurrence seem to be related to various factors in connection with solar and terrestrial phenomena and their states. As one of such factors it is pointed out that there is a case by case difference in an interaction between the geomagnetic field and the solar wind which may bring different magnetic field (IMF). Because the IMF plays an important role in the geomagnetic disturbance as one of the most important causative factors. However, any detailed factors or reasons to explain all the features of the geomagnetic storm occurrence have not been yet investigated.

4.2 Storm range of sg-storm

Annual distribution of the sg-storm range during the period from 1924 to 1982 is presented in Fig. 14. Also annual occurrence frequencies for four classes of the storm range are presented in the upper part.

The most outstanding feature seen in Fig. 14 is that the sg-storm ranges larger than 200 nT occur quite rarely and almost all of the storm ranges distribute within

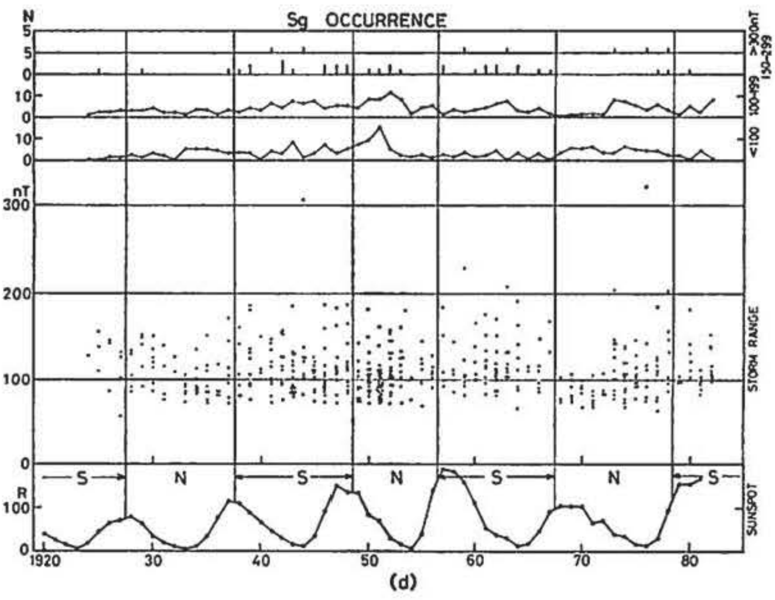



Fig. 14. Annual occurrence distribution of the sg storm range and annual occurrence frequencies for various classes.

a range smaller than 150 nT. Solar cycle dependence of the sg-storm range is not so clear as that of the sc-amplitude or the sc-storm range, though there seems to be roughly seen such a tendency as an upper boundary of distribution of the sg-storm range changes as a whole in accordance with the long-term trend of the sunspot number. As one of the most strange features it should be noted that the sg-storms with the storm range larger than about 110 nT did not occur during five years from 1968 to 1972, which correspond to the maximum and decreasing (beginning) sunspot phases, and suddenly came to be observed again since 1973. As already mentioned in the previous section, there is the other strange feature that the sg-storms occurred quite frequently in the decreasing sunspot phase of the 18th solar cycle. It can be seen from Fig. 14 that the above feature is mainly due to the frequent occurrence of the sg-storms smaller than 100 nT in storm range.

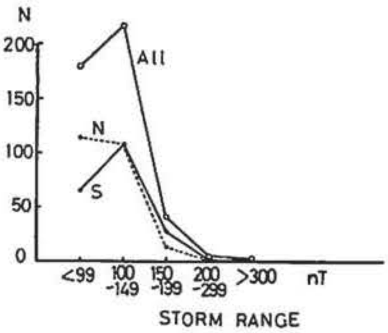



Fig. 15. Occurrence frequency distributions of the sg storm range for the whole period and for the S.P. and N.P. epochs.

While, it is hard to find clear S/N polarity asymmetry of the sg occurrence frequency and the storm range distribution, but there is a considerable difference between the occurrence frequencies of the sg-storm range smaller than 100 nT in the S.P. and N.P. epochs as shown in Fig. 15. This should be noticed as the greatest difference of the sg-storm occurrence feature between the two epochs.

4.3 A heliomagnetic polarity asymmetry in the seasonal variation of the geomagnetic storm occurrence frequency

It is well known that there is a seasonal variation of the geomagnetic storm occurrence frequency. It is very interesting to clarify whether there exist some significant differences in the feature of the seasonal variation for different epochs. Then, seasonal variations of the sc- and sg-storm occurrence frequencies are investigated by dividing the whole analyzed period into the S.P. and N.P. epochs.

In Fig. 16 is shown monthly total occurrence frequencies of the sc-storm for

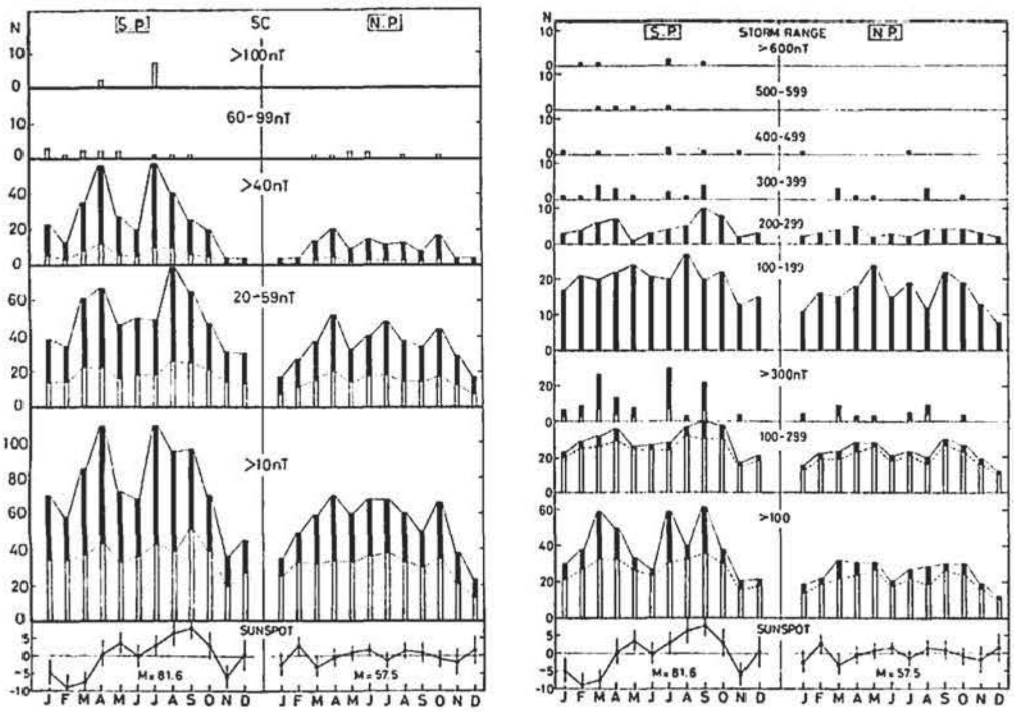



Fig. 16. Seasonal variations of the sc-storm occurrence frequency based on the sc-amplitude (left) and the storm range (right) for respective various classes. The black and white bars in each lower three classes indicate the respective weighted and simple occurrence frequencies.

various classes of the sc-amplitude (left) and the storm range (right), and for the S.P. and the N.P. epoch. For some of them both the simple and the weighted occurrence frequency are illustrated by a superposed expression. Besides, each mean seasonal variation of the sunspot number for the corresponding epochs is presented at the bottom of each figure. And, the sc-storms smaller than 10 nT in sc-amplitude and 100 nT in storm range are excluded so as to use only relatively reliable data in this analysis.

As can be seen in the left panel Fig. 16, the respective seasonal variations of the sc-amplitude occurrence frequencies show various meaningful differences between the two epochs and between different classes. Generally speaking, in both cases of simple and weighted occurrence frequencies a semi-annual variation is more predominant in the S.P. epoch and an annual one is predominant rather than the semi-annual one in the N.P. epoch. And it should be remarked that the seasonal variation in the N.P. epoch shows three maxima as a combination of the semi-annual and annual variations, in particular, in the class of 20–59 nT range. These meaningful differences between the two epochs cannot be well explained, but some conditions of the earth's ionosphere and magnetosphere seem to be related to them.

While, such a difference cannot be clearly found in the case for the storm range (the right panel of Fig. 16), but a semi-annual variation is more predominant in both N.P. and S.P. epochs. In other words, there is no great difference in the seasonal variation of the storm range occurrence frequency between the two epochs. On the contrary, the seasonal variation of the sunspot number is greatly different between the two epochs, showing a significant annual variation in the S.P. epoch, but no significant one in the N.P. epoch. This seasonal variation in the S.P. epoch has no close relationship with that of the sc-storm occurrence frequency, even though there is the close relationship between their year-to-year variations as discussed in section 3. This means that the seasonal variation of the storm occurrence frequency is not caused directly by that of the sunspot number itself, but is caused by some other factors, for example, by the apparent seasonal variation of direction of the solar rotation axis (apparent preccession of the equinoxes). This can be understood from a fact that there is a clear seasonal variation of the storm occurrence frequency in the N.P. epoch without any one of the sunspot number. However, this does not mean that there is not any sunspot number dependence in the seasonal variation of the storm occurrence frequency, but its dependence is much smaller than those of other factors. It should be referred for the above interpretation that the ratio of seasonal variation range ($\Delta$N) of the sunspot number against the annual mean value (N) is far smaller than that of the storm occurrence frequency even in the S.P. epoch ($\Delta N/N=$about $15/82=0.18=18\%$ in the former case, cf. $\Delta N/N=$about $20/25=0.8=80\%$ in the latter case).

As another outstanding feature, it is notable that the huge sc-storms occur mainly in the spring and summer equinoxes, especially the sc-amplitudes larger than 100 nT do only in July and April, though the total number of such huge storms is no more than seven.

Fig. 17 shows seasonal variations of the sg simple occurrence frequency in the S.P. and N.P. epochs and for the whole period. In this case the whole sg-storms are summed together, because of the smaller number of events than that of the sc-storm. As can be seen in the figure, all seasonal variations of the sg occurrence frequency show a clear semi-annual variation with two maxima in the spring and autumn equinoxes, being much more distinct than those of the sc-storm. And, there is not a great difference of the seasonal variation between the two epochs, except such a little difference as there seems to exist an equinox asymmetry in the S.P. epoch. It has been a well-known fact that the sg-storm has such a semi-annual variation in the occurrence frequency. This is well understood by the apparent seasonal precession of the solar rotation axis.

Besides, though the annual variation of the sg occurrence frequency is not so

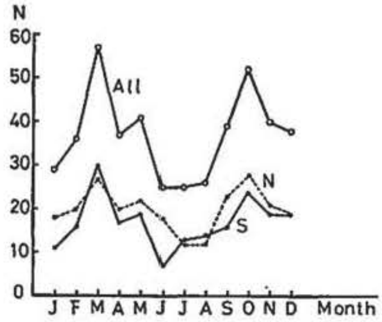



Fig. 17. Mean seasonal variations of the sg-storm occurrence frequency for the whole (All) and for the N.P. (N) and S.P. (S) epochs.

predominant as that of the sc-storm, it seems to have a summer minimum and a winter maximum. This is opposite in phase to that of the sc-storm. Such difference is very interesting, possibly being due to including relatively many ssc-like sg-storms in the winter with a small sc-amplitude as cannot be adopted as an sc. However, its details have scarcely investigated.

## 5. Concluding remarks

In this paper we have discussed the detailed occurrence features of the geomagnetic storms at Kakioka mainly as regards their differences for different solar cycles and different polarity epochs of the heliomagnetic field. Many significant differences have been found.

As for the sc-storm occurrence feature, the most outstanding fact is that there is such a significant S/N polarity asymmetry as the sc-storms larger than 300 nT in storm range or larger than 40 nT in sc-amplitude occur much more frequently in the S.P. epoch than in the N.P. epoch and vice versa in the feature normalized by the sunspot number. Especially, it should be noted that the huge sc-storms larger than 500 nT in the storm range or larger than 100 nT in sc-amplitude take place only in the former epoch. There is a good correlation as high as about 0.9 between the annual sc-storm occurrence frequency and the sunspot number. If some 10% deviated data are omitted, the correlation coefficient attains to about 0.95 or more. As such unusual epochs the 19th and 21st solar cycles are picked up. In addition to these features it should be remarked as another strange feature that the sc* occurrence frequency and its occurrence percentage against the sc's suddenly increased in 1956 and thereafter such state has continued until now on the average.

As for the sg-storm occurrence feature, a sudden decrease of the occurrence frequency in the 19th solar cycle is one of the most outstanding features. And, it is a significant feature that the sg-storms larger than 200 nT in storm range rarely occur and almost all of the sg-storm ranges distribute within the range smaller than 150 nT. In the case of sg-storm there seems to be an S/N polarity asymmetry or difference in the occurrence feature, though it is not so evident as in the case of sc-storm. This S/N polarity asymmetry or difference shows that there is an one-year phase difference in the maximum occurrence frequency between the S.P. and N.P. epochs.

On the other hand, although as a matter of course sg-storms occur most frequently in the late decreasing sunspot phase of the solar cycle, it is very interesting to note that a secondary maximum of the occurrence frequency seems to take place in the increasing sunspot phase, particularly in the N.P. epoch. In addition, the following fact should be remarked.

The sg occurrence frequency in each solar cycle seems to be as a whole proportional to the maximum sunspot number in each corresponding solar cycle, except in the 19th solar cycle. This may mean that the activity of the M-region or the coronal hole is related to the sunspot activity. Namely, the sunspot activity in the maximum phase in each solar cycle affects in general the sg-storm occurrence in the following decreasing sunspot phase. However, when the sunspot and flare activities become as extremely high as in the 19th solar cycle, this relation may be destroyed due to their control effect on the sg-storm occurrence.

In this way, although the occurrence feature of the geomagnetic storms is one of the most fundamental problems in geomagnetism and has been investigated for long years, its many new detailed features have been found out from the present study. Almost all of them are characteristics concerning to the solar cycle and the heliomagnetic polarity dependence in the storm occurrence feature. In order to make them much surer, further detailed study using much more data for much longer period needs.

## Acknowledgements

The authors would like to express their thanks to Dr. A. Harada, the director of the Kakioka Magnetic Observatory, for his advice and encouragement.

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# 柿岡における磁気嵐出現の経年および太陽周期変化

佐野幸三・斎藤龍雄

## 概要

磁気嵐の出現特性については，古くからいろいろと解析されてきたが，今回筆者らは1924～1981年までの資料を用いて，その経年変化・太陽周期依存性を統計的に詳細に調査したので報告する。主な結果は次のとおりである。

1) 急始磁気嵐（SSC）は，太陽磁場極性による出現非対称性を示す。磁気嵐の出現数を太陽黒点数の函数としてみた場合，大規模磁気嵐は太陽磁場がS極性期間により多く，小規模なものはN極性期間により多く出現する。特に巨大磁気嵐（SC振幅＞100 nT，変化較差＞500 nT）はS極性期間のみに出現している。
2) 急始磁気嵐出現数と太陽黒点数は一般に高い相関を示すが，近年の21サイクルではこの関係がかなり乱れている。
3) 緩始磁気嵐（Sg）は太陽黒点減少期後期に多発するが，太陽磁場のN, S極性期間に，ピーク出現年に約1年程度の差がありそうである。また，太陽黒点増加期にも，小さい2次的な出現数のピークがありそうである（特にN極性期）。
4) 緩始磁気嵐も太陽黒点数（活動度）依存性が認められるが，19サイクル（今世紀太陽活動度最大）期にはこの関係が乱れ，緩始磁気嵐の出現が急減している。
5) その他，1956年よりSC* の出現数および出現率が急増していることが特筆される。