2. *The Geomagnetic D_{st} Field of the Magnetic Storm on June 18-19, 1936.*

By Tsuneji RIKITAKE and Setsuko SATO,

Earthquake Research Institute.

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Summary

The D_{st} part of the magnetic storm on June 18–19, 1936 is examined with the aid of many copies of magnetograms sent from well-distributed observatories. It is found that the relation between the external origin and internal origin parts of the D_{st} field is well explained by the electromagnetic induction within the earth, of which the distribution of the electrical conductivity is taken as the one obtained by one of the writers.

1. Introduction

S. Chapman and A. T. Price[1] analysed the storm-time variation or D_{st} field of magnetic storms. The relation between the external origin and internal origin parts was obtained by them by use of spherical harmonic analysis. It was made clear that the magnetic potential of the D_{st} field in the low and middle latitude can be expressed as a combination of a few zonal harmonics of low degree, because the field does not depend on longitude. Among these harmonics, however, the term including $P_1(\cos\theta)$ is so large that the other ones such as $P_3(\cos\theta)$ and $P_5(\cos\theta)$ can be almost ignored.

The physical interpretation, which is based on the theory of electromagnetic induction within the earth, of the relation between both the parts led to an important conclusion that the electrical conductivity of the deeper part of the earth is to be larger than that of the shallow region whose conductivity has been estimated from analyses of the S_q variation. Chapman and Prices' study was followed by others concerning the electromagnetic induction within a non-uniform earth[2),3)]. As a result of these studies, the distribution of the electrical conductivity is

1) S. CHAPMAN and A. T. PRICE, *Phil. Trans. Roy. Soc. London A*, **229** (1930), 427.
2) B. N. LAHIRI and A. T. PRICE, *Phil. Trans. Roy. Soc. London A*, **237** (1939), 509.
3) T. RIKITAKE, *Bull. Earthq. Res. Inst.*, **28** (1950), 45, 219, 263; **29** (1951), 61.

Table I. List of the observatories.

Observatory	Abbreviation	Geographic latitude	Geographic longitude	Geomagnetic latitude	Geomagnetic longitude
Godhavn	GO	69°.2	306°.5	79°.8	32°.5
Tromsö	TR	69.7	18.9	67.1	116.7
Sodankylä	SO	67.4	26.6	63.8	120.0
Lerwick	LE	60.1	358.8	62.5	88.6
Eskdalemuir	ES	55.3	356.8	58.5	82.9
Lovö	LO	59.4	17.8	58.1	105.8
Rude Skov	RS	55.8	12.4	55.8	98.5
Wilhelmshaven	WL	53.5	8.2	54.5	92.9
Abinger	AB	51.2	359.6	54.0	83.3
De Bilt	DB	52.1	5.2	53.8	89.6
Val Joyeux	VJ	48.8	2.0	51.3	84.5
Wien	VI	48.2	16.2	47.9	98.1
San Miguel	SM	36.6	101.4	45.6	334.4
Ebro	EB	40.8	0.5	43.9	79.7
San Fernando	SF	36.5	353.8	41.0	71.3
Helwan	HE	29.9	31.3	27.2	106.4
Cape Town	CT	−33.9	18.5	32.7	79.9
Sitka	SI	57.0	224.7	−60.0	275.4
Cheltenham	CH	38.7	283.2	50.1	350.5
Tucson	TU	32.2	249.2	40.4	312.2
San Juan	SJ	18.4	293.9	29.9	3.2
Teoloyucan	TE	19.7	260.8	29.6	327.1
Honolulu	HO	21.3	201.9	21.1	266.5
Huancayo	HU	−12.0	284.7	− 0.6	353.8
Pilar	PI	−31.7	296.1	−20.2	4.6
Toyohara	TY	47.0	142.8	36.9	203.5
Kakioka	KA	36.2	140.2	26.0	206.0
Dehra Dun	DD	30.3	78.0	20.5	149.9
Alibag	AL	18.6	72.9	9.5	143.6
Apia	AP	−13.8	188.2	−16.0	260.2
Kuyper	KU	− 6.0	106.7	−17.5	175.5
Watheroo	WA	−30.3	115.9	−41.8	185.6
Toolangi	TO	−37.5	145.5	−46.7	220.8
Christchurch	CR	−43.5	172.7	−47.7	252.5

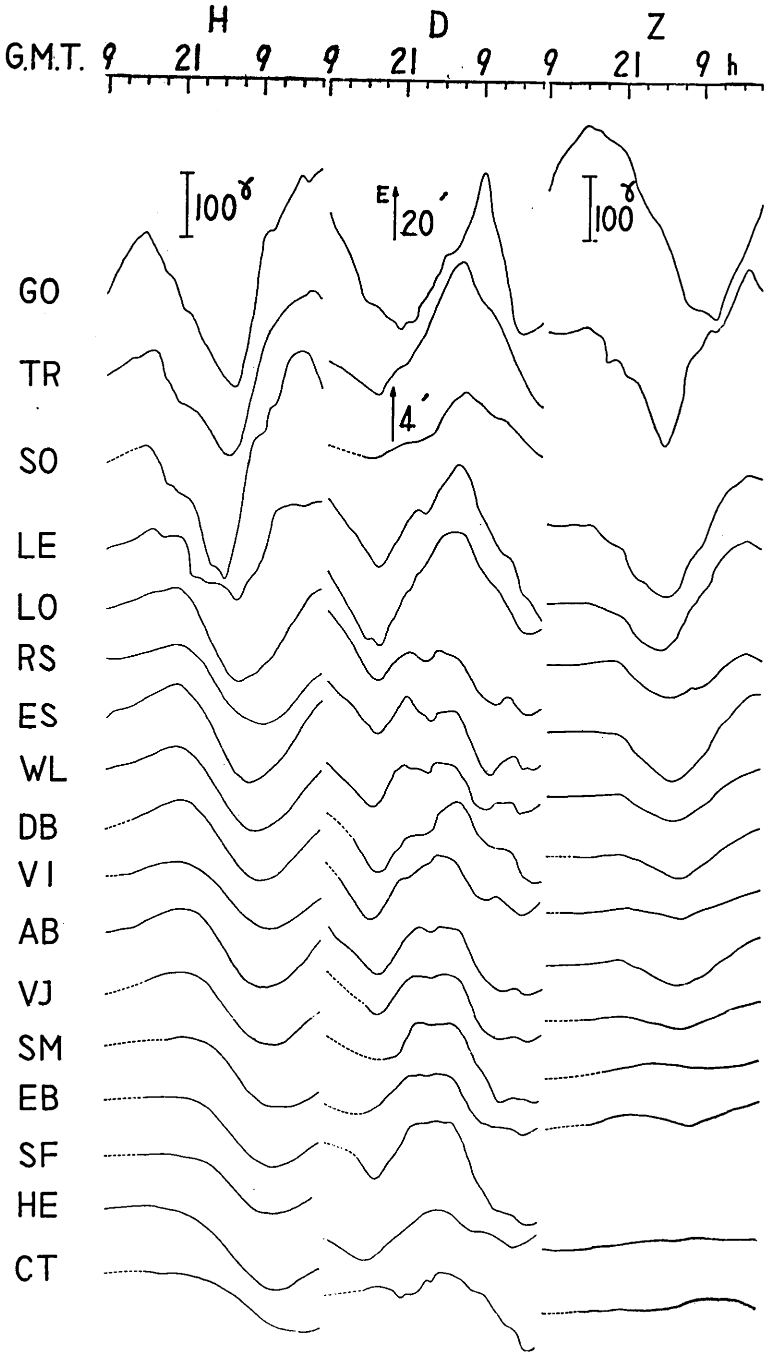

Fig. 1. The running averages of the D_{st} field for the observatories in Europe and Africa.

approximately obtained down to a depth of about 1500 *km*.

Since only the analysis of the D_{st} due to Chapman and Price has been hitherto available, however, it has been hoped to make another analysis of the D_{st} in order to check the abovementioned distribution of the electrical conductivity. In relation to the examination of the anomalous features of short-period geomagnetic variations in Japan, the writers had a chance to collect copies of magnetograms during a particular magnetic storm that occurred on June 18–19, 1936. These copies of magnetograms will be useful for making a new analysis of the D_{st} field, though nothing definite has been obtained yet about the local irregular behaviour of the D_{st} as has been found in the case of the S_q and bays n Japan.

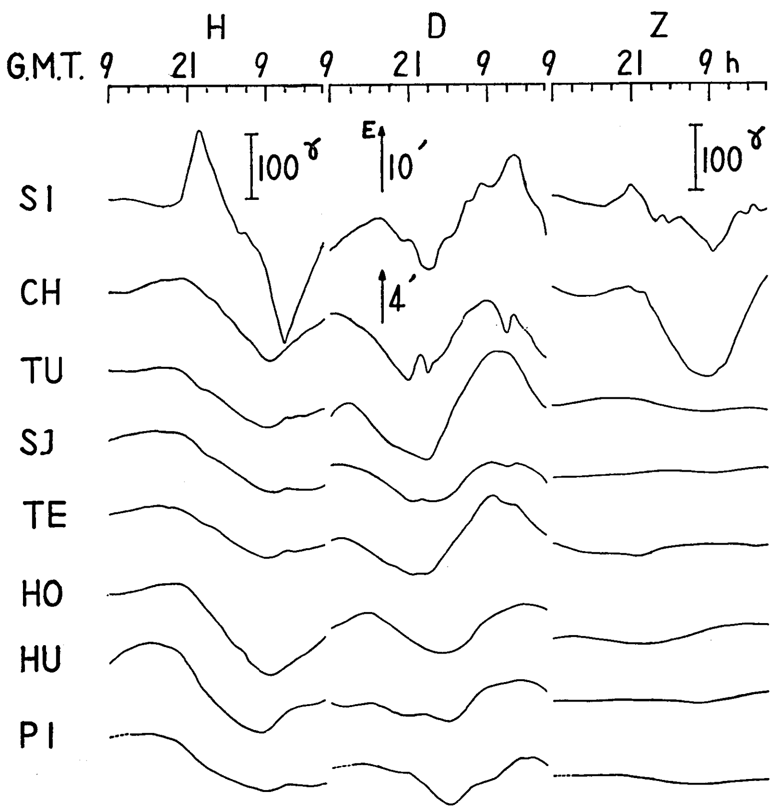

Fig. 2. The running averages of the D_{st} field for the observatories in America.

2. Data

A magnetic storm with a SC occurred at 9 *h* 41 *m* GMT on June 18, 1936. The initial phase of the storm lasted as long as 10 *hours* when the decrease of the horizontal intensity associated with the main phase of the storm took place, while the maximum decrease amounted to 200 *gammas* at middle latitude observatories. After 10 *h* GMT on June 19, the storm seemed likely to enter its recovery phase.

Copies of magnetograms on June 18-19 were kindly sent to the writers from many observatories at the writers' request. The observatories with whose data the writers carried out the present study are shown in Table I.

Since we are interested in variations of comparatively longer period,

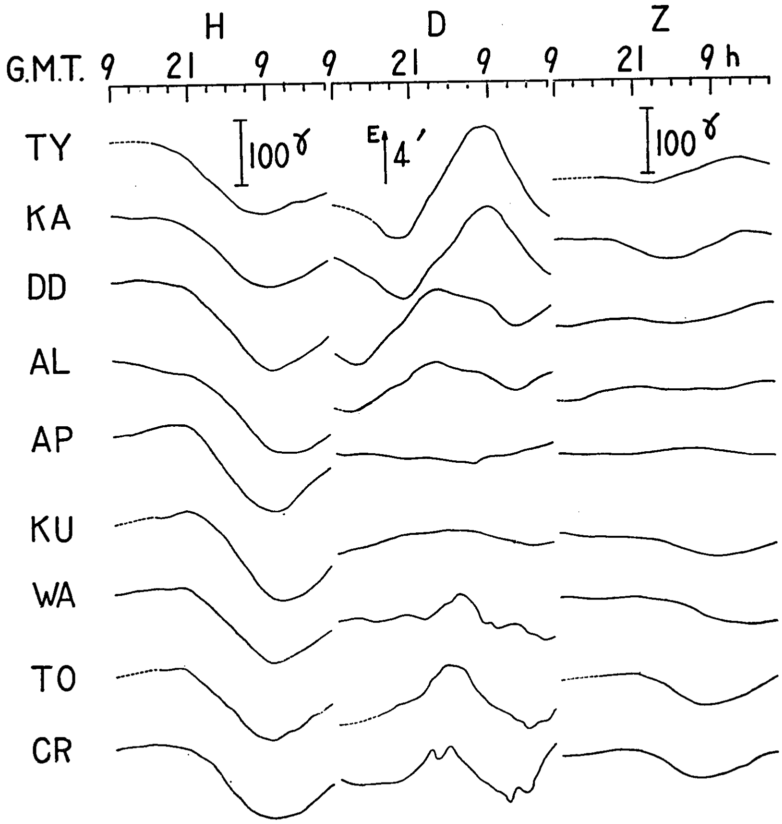

Fig. 3. The running averages of the D_{st} field for the observatories in Asia and Australia.

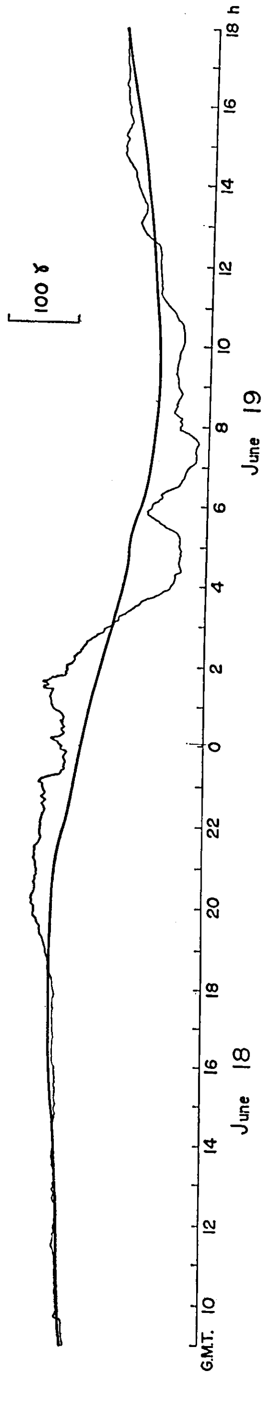

Fig. 4. The original record and the running average of the H-curve at Honolulu.

running averages of H (horizontal intensity), D (declination) and Z (vertical component) are made at all the observatories. From the readings of hourly values of the respective components, the averages of 13 readings are calculated. The values thus obtained are regarded as the values at the centred time of the averaged interval. The results are shown in Figs. 1, 2 and 3 respectively at the observatories in Europe and Africa, America, and Asia and Australia. A comparison of the original record to the running average is shown in Fig. 4 in which we see that short-duration changes having periods of a few *hours* are nearly eliminated because of the characteristics of the running average procedure.

Although it is difficult to determine the normal state of the earth's magnetic field which is free from the influence of the magnetic storm, we may assume that the values at 9 h GMT represent the normal state. The errors due to the S_q and other geomagnetic variations are safely disregarded, because the amplitude of the main phase is fairly large. The departures of the respective components from the 9 h values are obtained. From these, the departures of the geomagnetic north (ΔX_m) and geomagnetic east (ΔY_m) components are calculated. ΔX_m is shown in Table II for every 4 *hours* after 9 h GMT on June 18. The departures of the vertical component (ΔZ) are also shown in Table III in the same way.

As can be seen in Figs. 1, 2 and 3, the variations of the horizontal intensity show a typical course of magnetic storms which has been studied in detail in the morphology of magnetic storms. Although it is beyond the scope of the present paper to study various features of the storm, the overhead equivalent

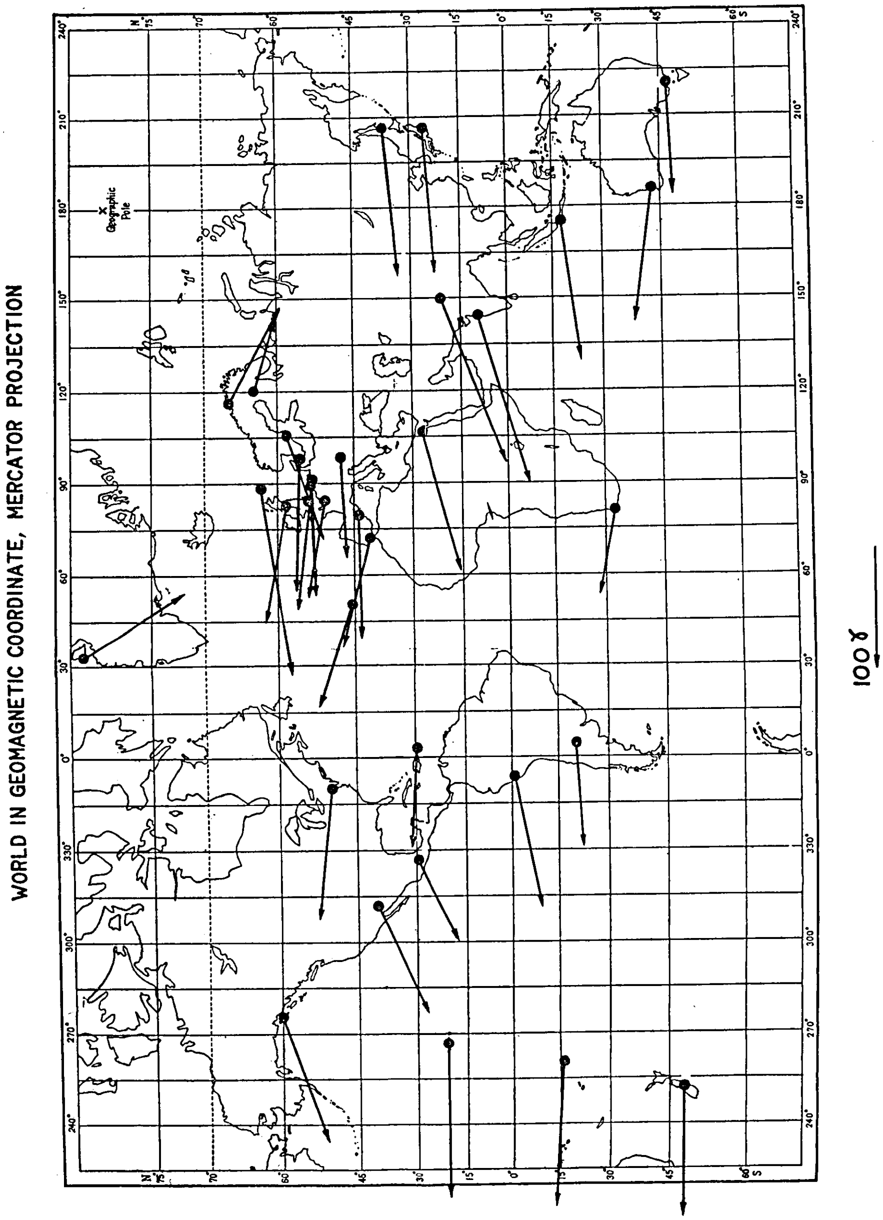

Fig. 5. The disturbance field at 9*h* GMT on June 19 as expressed by the equivalent current arrows.

Table II. ΔX_m in *gamma*.

Observatory	0*h*	4*h*	8*h*	12*h*	16*h*	20*h*	24*h*	28*h*	32*h*
VI	0.0	1.5	12.3	19.1	− 2.7	− 47.2	− 79.8	− 73.7	− 39.2
SM	0.0	4.9	9.4	13.6	1.5	− 40.7	− 83.0	− 87.9	− 74.9
EB	0.0	1.5	4.0	3.0	−14.4	− 61.5	− 98.8	−101.0	− 73.8
SF	0.0	0.0	3.4	− 1.4	−13.8	− 54.1	− 87.1	− 88.4	− 91.2
HE	0.0	−1.5	−1.1	− 7.6	−30.3	− 73.0	−112.8	−120.6	− 97.0
CT	0.0	1.8	0.8	− 0.9	−12.7	− 34.6	− 69.2	− 82.2	− 81.2
TU	0.0	0.3	4.4	− 9.1	−39.5	− 67.8	− 86.7	− 72.3	− 62.3
SJ	0.0	11.4	15.4	7.0	−24.9	− 53.8	− 80.7	− 76.3	− 73.4
TE	0.0	6.8	11.7	0.9	−23.5	− 50.6	− 65.5	− 58.1	− 50.4
HO	0.0	4.0	14.8	9.5	−37.4	− 84.6	−125.2	−109.3	− 76.8
HU	0.0	25.7	27.8	− 3.5	−61.9	− 97.5	−104.9	− 70.5	− 60.5
PI	0.0	6.8	1.5	−21.1	−54.3	− 74.9	− 83.4	− 74.2	− 74.5
TY	0.0	3.3	0.1	−21.3	−66.7	−106.8	−121.1	− 95.9	− 79.3
KA	0.0	−1.8	−0.8	−14.4	−52.2	− 97.8	−116.7	−102.8	− 75.0
DD	0.0	2.0	0.2	− 7.9	−46.7	− 94.7	−131.5	−118.7	−106.7
AL	0.0	−7.6	16.9	−21.4	−47.4	− 92.5	−136.0	−141.2	−121.0
AP	0.0	6.5	17.1	12.0	−38.7	− 92.5	−115.9	− 94.7	− 58.5
KU	0.0	7.2	13.1	20.0	−10.4	− 62.6	−111.6	−110.7	− 78.4
WA	0.0	5.2	7.3	2.5	−34.0	− 75.0	−106.6	− 91.4	− 64.5
TO	0.0	7.0	11.4	1.5	−35.4	− 78.6	− 90.1	− 80.3	− 51.9
CR	0.0	5.7	6.3	− 3.7	−39.5	− 89.8	−104.3	− 98.9	− 63.5

current arrows are obtained as shown in Fig. 5, for instance, at 9*h* GMT on June 19 when the D_{st} field seems to reach its maximum. In Fig. 5, we can see that the D_{st} field is expressed by overhead electric currents flowing from the east to the west in the low and middle latitude. At high latitude, however, there is an irregular distribution of the arrows which is probably due to the S_D field, though its detailed behaviour can not be examined here owing to the lack of data.

3. Analysis

The distribution of the D_{st} field as can be seen in Figs. 1, 2, 3 and 5 suggests that the magnetic potential of the field may be approximately expressed by a series of zonal harmonics such as

$$W=a\sum_n \{e_n(t)(r/a)^n+i_n(t)(a/r)^{n+1}\}P_n(\cos\theta)\ , \qquad (1)$$

where a and θ denote respectively the earth's radius and the colatitude

Table III. ΔZ in *gamma*.

Observatory	0*h*	4*h*	8*h*	12*h*	16*h*	20*h*	24*h*	28*h*	32*h*
VI	0.0	0.3	− 1.8	6.3	0.5	− 5.3	6.0	19.9	33.0
SM	0.0	6.0	10.0	17.8	24.7	23.1	19.0	19.5	28.3
EB	0.0	4.8	10.4	21.8	20.1	11.9	10.0	28.0	41.6
SF	—	—	—	—	—	—	—	—	—
HE	0.0	− 1.4	4.0	9.0	14.5	16.1	20.9	18.1	19.9
CT	0.0	3.0	6.9	9.2	5.9	13.5	25.0	26.8	19.3
TU	0.0	5.3	10.3	8.2	0.4	− 7.7	18.0	− 6.5	− 7.5
SJ	0.0	0.2	2.6	5.3	8.2	7.7	−12.8	8.5	−11.6
TE	0.0	−11.3	−15.0	−18.7	− 9.7	4.0	10.2	− 1.7	− 3.4
HO	0.0	1.5	− 4.0	− 8.5	− 8.5	1.7	14.0	18.6	20.0
HU	0.0	− 0.4	1.3	0.9	1.0	− 1.6	1.7	5.7	10.8
PI	0.0	0.4	0.9	− 0.8	− 7.3	−10.9	−37.2	− 7.9	− 6.5
TY	0.0	2.0	− 0.7	− 7.2	− 8.3	4.1	−37.9	26.7	18.5
KA	0.0	− 0.4	− 1.8	−16.1	−30.3	−28.5	−39.0	5.5	4.1
DD	0.0	3.8	8.5	7.5	1.6	3.5	−29.6	22.3	29.7
AL	0.0	7.0	16.8	21.1	14.9	15.6	−10.5	31.3	25.0
AP	0.0	− 2.4	− 3.8	− 1.9	2.5	5.2	5.7	− 3.9	− 6.6
KU	0.0	− 5.7	− 7.4	− 8.6	16.6	−29.7	4.0	−32.2	−21.6
WA	0.0	− 2.9	− 2.8	− 2.9	− 6.3	−20.1	12.6	−42.3	−40.9
TO	0.0	3.7	6.1	5.6	−12.5	−36.6	− 1.2	−25.7	− 1.9
CR	0.0	3.8	8.9	7.2	−12.2	−32.9	−12.0	−17.6	2.3

in the geomagnetic coordinate. e_n and i_n correspond respectively to the coefficients of the harmonics, the former being due to the external origin part while the latter due to the internal origin one. The expression is exactly the same as that adopted by Chapman and Price[1]. As has been also shown by them, the term for $n=1$ is to be quite large, so that the other terms are neglected in the following. In that case, we obtain, from (1), the components of the magnetic field as follows:

$$\left.\begin{aligned} \Delta X_m &= -(e_1+i_1)\sin\theta\,, \\ \Delta Z &= (e_1-2i_1)\cos\theta\,. \end{aligned}\right\} \quad \text{at} \quad r=a\,. \qquad (2)$$

Since ΔX_m and ΔZ for respective observatories are given in Table II and III, we can determine e_1+i_1 and e_1-2i_1 by making use of the least square method. For illustration, the relations between ΔX_m and ΔZ and geomagnetic latitude at 9 *h* GMT on June 19 are shown in Fig. 6 in which the curves defined by (2) are also illustrated. The coefficients thus determined are shown in Table IV for respective times, so that we can calculate e_1 and i_1 separately as are also shown in the table together with their probable errors. In these analyses, only the observatories situated between 50°N and 50°S are taken into consideration in order to avoid the influence of S_D that predominates at high latitude. The time variations of e_1 and i_1 are illustrated in Fig. 7. At a glance, we

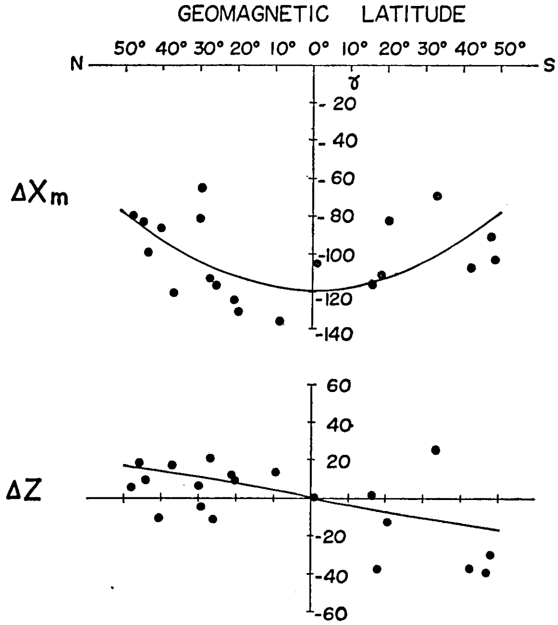

Fig. 6. The distribution of ΔX_m and ΔZ at $9h$ GMT on June 19.

Table IV. The coefficients at every 4 *hours* and their probable errors. (Unit: *gammas*)

Storm time	e_1+i_1	e_1-2i_1	e_1	i_1
0^h	0.0	0.0	0.0	0.0
4	-5.3 ± 4.2	1.1 ± 3.0	-3.2 ± 3.0	-2.1 ± 1.7
8	-10.2 ± 5.0	1.8 ± 5.3	-6.2 ± 3.8	-4.0 ± 2.4
12	1.7 ± 8.3	3.2 ± 7.6	2.2 ± 6.1	-0.5 ± 3.8
16	39.6 ± 11.7	6.4 ± 8.7	28.5 ± 8.3	11.1 ± 4.7
20	86.8 ± 13.0	16.4 ± 10.7	63.3 ± 9.4	23.5 ± 5.6
24	119.4 ± 12.6	21.8 ± 11.3	86.9 ± 9.2	32.5 ± 5.6
28	110.0 ± 13.4	27.3 ± 11.0	82.4 ± 9.7	27.6 ± 5.8
32	88.1 ± 11.6	23.6 ± 12.1	66.6 ± 8.7	21.5 ± 5.6

see that the relation between e_1 and i_1 closely resembles the one obtained by Chapman and Price[1)].

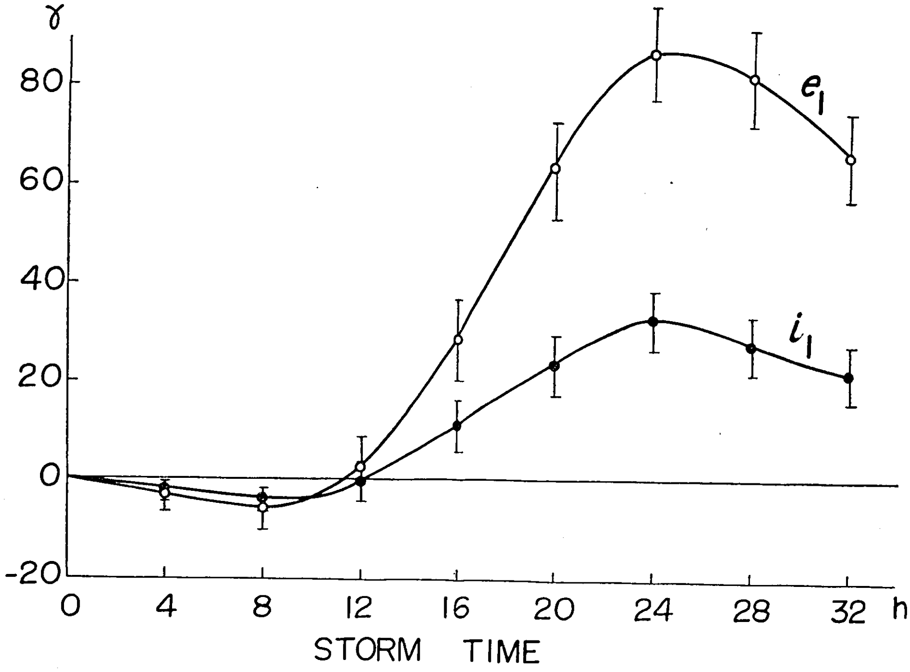

Fig. 7. The most probable values of e_1 and i_1 at every 4 *hours*. The probable errors are also shown.

4. Physical interpretation of the relation between e_1 and i_1

The theory of the electromagnetic induction in the earth has been successful in interpreting the relation between the external origin and the internal origin parts of geomagnetic variations. By applying the theory to the results of analyses of various variations, slow and rapid, the distribution of the electrical conductivity in the earth has been approximately obtained by the senior writer of the present paper. In this section, the writers would like to examine how well the conductivity distribution can explain the relation between e_1 and i_1 obtained in the previous section. Since no such analysis of the D_{st} field has been published since Chapman and Prices' study, this sort of check of the conductivity distribution will be desirable.

In so far as we take the standpoint that the internal origin part is induced by the inducing field of external origin, the relation between the inducing and induced fields is given as

$$i_1(t)=\frac{d}{dt}\int_0^t e_1(t-u)h(u)du \tag{3}$$

or

$$i_1(t)=e_1(t)h(0)+\int_0^t e_1(t-u)h'(u)du\ . \tag{4}$$

If we assume that the conductivity in the earth is given by

$$\sigma=\sigma' \quad \text{for} \quad 1>r/a>q\ ,$$
$$\sigma=\sigma_0(r/a)^{-l} \quad \text{for} \quad q>r/a>0\ ,$$

where $\sigma'=10^{-15}\,emu$, $\sigma_0=1.0\times10^{-12}\,emu$, $l=11$ and $q=0.94$ as obtained before. $h(t)$ in (3) or (4), which corresponds to the field induced by the inducing field given as a unit function, has been already obtained in the previous paper[3]. The change in $h(t)$ with time is reproduced in Fig. 8.

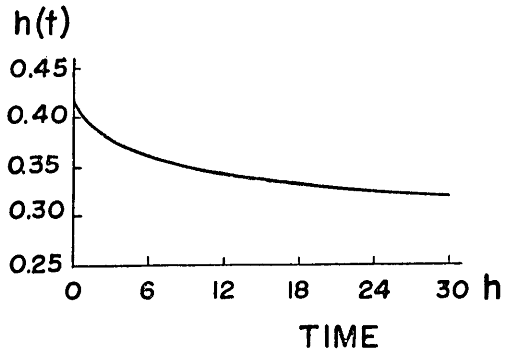

Fig. 8. The change in $h(t)$.

Now, we can obtain $i_1(t)$ for any time by means of numerical integration, because $e_1(t)$ is given in the last section. The result of the calculation is shown in Fig. 9 in whihc $i_1(t)$ at every 4 *hours*, which is obtained by the analysis, is also plotted. The agreement between the calculated curve and the values obtained from the analysis is striking, so that we may say that the distribution of the electrical conductivity obtained before is in good harmony with the present analysis of the D_{st} field.

5. Concluding remarks

It is made clear that the relation between the external origin and the internal origin parts of the D_{st} field of a magnetic storm that occurred on June 18–19, 1936 is well explained by the theory of electromagnetic induction within the earth, provided we assume the electrical conductivity distribution in the earth which has been obtained by one

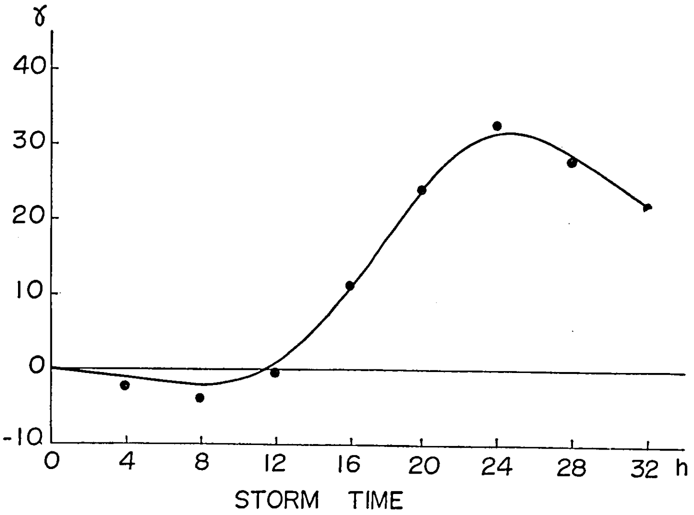

Fig. 9. The calculated values of i_1 are shown by the curve, while the values obtained from the analysis are shown by the small circles.

of the writers. We may now consider that the said distribution will give a reliable approximation of the averaged electrical state of the earth. The writers have collected many copies of magnetograms in the hope of investigating the local anomalous behaviours of geomagnetic variations in Japan. The investigations have been successful for short-period variations. An interesting result concerning the distribution of the electrical conductivity underneath Japan has been derived from the investigations. It is highly desirable to make the same sort of investigation on the D_{st} field, because there would be a possibility to infer the electrical state deeper than the one examined by short-period variations. However, the writers have not been able to accomplish such an investigation because magnetograms for the whole period of the storm have been supplied from very few observatories in and around Japan. Investigations on local anomalous feature of the D_{st} field, therefore, will be left to the future though a plausible approximation is obtained for the averaged distribution of the electrical conductivity in the earth.

In conclusion, the writers are grateful to Mr. I. Yokoyama who has constantly helped them in the course of the study. The present study was done with many copies of magnetograms which were sent to the writers from many observatories at the writers' request. The writers wish to express their cordial thanks to the following persons :

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2. 1936年 6月 18日～19日の磁気嵐の D_{st} 場

地震研究所 {力武常次 / 佐藤節子}

世界各地の観測所より送られた記録を解析して，1936 年 6月 18～19 日 の磁気嵐の D_{st} 場について解析を行つた，13 ケの毎時の読みの平均をとることによつて短周期変動を除去した結果について，地球外および内に原因を有する部分に分離したところ，すでに Chapman および Price 等によつて求められている結果とほぼ同様な結果が求められた．この両部分の関係を理解するために，筆者の一人によつて求められたような電気的性質を有する地球内への電磁感応を調べてみると，地球内より発生する部分は理論的誘導電流のつくる磁場と全く一致することがわかつた．
