Superposed Epoch Analyses of Geoelectric Field Disturbances in Japan in Response to Different Geomagnetic Activities

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Abstract An increase in geomagnetically induced currents (GICs) is an inevitable result of geomagnetic field disturbances, and is harmful to the power grid, in particular, at high latitudes. At mid and low latitudes, the amplitude of the GICs is, in general, small, but large-amplitude GICs are often observed during magnetic storms. It is of importance to understand major characteristics and extreme values of GICs at mid and low latitudes. For the geoelectric field disturbances $\Delta E$ observed at Kakioka (27.8° geomagnetic latitude) in Japan in 1996–2004, we performed superposed epoch analyses with respect to three types of geomagnetic disturbances: (a) storm sudden commencements (SSCs)/sudden impulses (SIs), (b) main phase of magnetic storms, and (c) bay disturbances. It is shown that the SSCs/SIs and the main phase of the magnetic storms are equally important for causing large-amplitude disturbances of $\Delta E$ at Kakioka. GICs are thought to be amplified when the SIs and/or the bay disturbances occur during the magnetic storms. The maximum value of $\Delta E$ tends to be correlated with the maximum value of $\Delta H$ during the three types of events, where $\Delta H$ is the horizontal component of the geomagnetic field. Assuming that a quasi-linear relationship between the maximum $\Delta E$ and the maximum $\Delta H$ is valid, we estimated GICs at three substations in Japan for an extreme SSCs/SIs, and the extreme magnetic storms. This scheme could be applicable to estimate roughly the GICs against extreme events, and to forecast the maximum GICs in a real-time manner.

Plain Language Summary Geomagnetic fields are known to change in characteristic manners during the magnetic storms and substorms. However, characteristic changes in the geomagnetically induced electric fields on the ground are not well known. We performed superposed epoch analyses of the electric field disturbances observed at Kakioka Magnetic Observatory in Japan to obtain an overview of the effects of associated electric current systems in near-Earth space on the electric field and geomagnetically induced currents (GICs). Histograms of the maximum amplitude of the electric field are also provided. The correlation between changes in the horizontal component of the geomagnetic field and the electric field is found to be good for each type of disturbance. Using empirical equations to indicate the relationship between them, we can roughly estimate the maximum electric field at Kakioka and GICs flowing at three electrical substations in Japan for extreme disturbances.

1. Introduction

Geomagnetically induced current (GIC) is a major concern at high latitudes, in particular, geomagnetic latitudes larger than 50° (Ngwira et al., 2013; Pulkkinen et al., 2012). Observations have shown that large-amplitude GICs also flow at geomagnetically low latitudes. For example, 55.8 A of GIC was recorded in the Chinese power grid during the 9 November 2004 magnetic storm (Liu et al., 2009). During the 28–30 October 2003 magnetic storm, 129 A of GIC was recorded in the Japanese power grid (METI, 2015). Ebihara et al. (2021) estimated that 89 ± 30 A of GIC flows at a particular substation in the Japanese power grid if the Carrington-class event occurs again. Note that the estimated value is the lower limit, so that larger GICs may flow at other substations in Japan. These observations and estimation suggest that the power grids at low latitudes may also face the risk against the GICs. While technical efforts have been conducted to prevent potential risk (e.g., Etemadi & Rezaei-Zare, 2014; Guo et al., 2015; Lesher et al., 1994; Lu et al., 2018; Overbye et al., 2013), quantitative estimation of the largest GICs is awaited to design the technical system and conduct a proper operation of the power grid. GICs flow in long, low-resistivity conducting lines connecting to the Earth. According to Faraday's law, the change in the magnetic field ($\delta B/\delta t$) induces the electric field ($E$) in the conducting lines and in the Earth, driving the current. The time derivative of the geomagnetic field ($\delta B/\delta t$) is often used to evaluate the geomagnetically induced electric fields (GIEs) and the GICs (e.g., Dimmock et al., 2020; Engebretson et al., 2021; Groom &
Table 1: Coefficients, a, b, and c for Substations SFS, STB, and SFJ (Ebihara et al., 2021)

| Substation       | a (A)  | b (A/(mV/km)) | c (A/(mV/km)) |
|------------------|--------|---------------|---------------|
| Shin-Fukushima (SFS) | -0.80  | -0.0892       | 0.0602        |
| Shin-Tsukuba (STB)  | 0.02   | 0.0195        | -0.0133       |
| Shin-Fuji (SFJ)     | -0.32  | -0.303        | 0.0422        |

For a certain power grid, it is known that GICs can be reasonably expressed by a linear combination of the two components of the GIEs (Ebihara et al., 2021; Pulkkinen et al., 2007; Viljanen et al., 2004; Zhang et al., 2020) as

\[
\text{GIC}(t) = a + b\Delta E_x(t) + c\Delta E_y(t),
\]

where \(\Delta E_x\) and \(\Delta E_y\) are the GIEs in the north-south and the east-west components, respectively, and \(a\), \(b\), and \(c\) are parameters likely depending on the topology of the network and resistance of it. \(a\) refers to an offset, probably including noise (Pulkkinen et al., 2007). With known GIEs and parameters \((a, b, \text{ and } c)\), one can calculate GICs with sufficient accuracy. Ebihara et al. (2021) derived the parameters for Shin-Fukushima (SFS), Shin-Tsukuba (STB), and Shin-Fuji (SFJ) substations. These substations are connected to the 500 kV power transmission lines, and are located in a suburban area of Tokyo, Japan (27°–29° geomagnetic latitudes). The parameters are summarized in Table 1. With the parameters and the GIEs observed at the Kakioka observatory, the calculated GICs at the three substations are well correlated with the observed ones with correlation coefficients of 0.91, 0.91, and 0.81, respectively. Ebihara et al. (2021) focused on three magnetic storms. For example, the maximum GICs are expected to be 14.4, 3.3, and 16.7 A at SFS, STB, and SFJ, respectively, during the 13 March 1989 magnetic storm.

Watari et al. (2021) showed that the GICs at STB and SFJ increase in accordance with different types of geomagnetic variations, including (a) storm sudden commencements (SSCs) and sudden impulses (SIs), (b) storm main and recovery phases, (c) bay disturbances, and (d) solar flare effect (SFE). The ultimate source of these variations is the Sun, but the current systems involved and the physical processes differ from type to type.

1. SSCs and SIs are known to occur when the solar wind dynamic pressure rapidly increases. When the magnetosphere is compressed, the magnetopause current flowing eastward is intensified, resulting in a positive deflection of the horizontal component of the geomagnetic field \(H\). This type of deflection is called a DL-field (Araki, 1994). The compression of the dayside magnetosphere also launches magnetohydrodynamics (MHD)
waves propagating anti-sunward. In the course of the propagation, field-aligned currents are excited, which are connected to the ionosphere. The resultant ionospheric current deflects $H$, called a DP field (Araki, 1994). The DL-field is significant at low-latitudes, whereas the DP-field is significant at auroral latitudes (Araki, 1994). The rise time of the SSCs/SIs ranges from $\sim 1$ to $\sim 12$ min, and the rate of change in the horizontal component of the geomagnetic variation increases with the peak amplitude of it (Araki et al., 2004). $\partial B/\partial t$ is shown to increase just after SSCs/SIs from high latitudes to the magnetic equator (Carter et al., 2015, 2016). Carter et al. (2016) discriminated between the magnetospheric contribution and the ionospheric contribution, and discussed the impact on GICs.

2. The negative deflection of $H$ lasting for a few days is called a geomagnetic storm (Gonzalez et al., 1994). The variations are caused by the storm-time ring current (Burton et al., 1975; Ebihara & Ejiri, 2003 and references therein). The contribution from the tail current is also suggested (Ohtani et al., 2001). When the southward component of the interplanetary magnetic field being less than $\sim 10$ nT lasts for 3 hr, intense magnetic storms with minimum $Dst$ less than $\sim 100$ nT occur with a probability of 80% (Gonzalez et al., 1994).

3. At high latitudes, $H$ rapidly decreases owing to the development of the westward auroral electrojet during the expansion phase of a substorm. At mid and low latitudes, the contribution from the auroral electrojet is small, but the contribution from the field-aligned current is thought to cause a positive excursion of $H$, known as a positive bay (Akasofu & Meng, 1969; McPherron et al., 1973; Meng & Akasofu, 1969). It has been believed that the field-aligned current is part of the substorm current wedge (Kepko et al., 2015), in which a large-amplitude field-aligned current flows into the ionosphere on the dawnside, and out of the ionosphere on the duskside. The mid-latitude positive bay rapidly rises to a peak in $\sim 20$ min, followed by a gradual decay (McPherron & Chu, 2018).

Woodroffe et al. (2016) presented the latitudinal distribution of $\Delta B$, $\partial B/\partial t$ and $E$ from 20° to 75° magnetic latitudes for different storm intensity in terms of $Dst$. The electric field $E$ was calculated by using the six-layer ground conductivity model (Boteler, 2015). They showed that the large-amplitude geomagnetic disturbances ($\partial B/\partial t > 5$ nT/s) can occur as low as 45°–55° magnetic latitudes during severe and extreme storms. At magnetic latitudes of 45°–55°,100-year geomagnetic disturbance $\Delta B$ is 738–1,987 nT. The electric field $E$ frequently exceeds 1 V/km during strong and severe storms at $\geq 50°$ geomagnetic latitude.

The aims of this research are to understand the major causes of large-amplitude the electric fields and GICs and the occurrence distribution of them at low latitudes on the basis of the electric field observed the Kakioka observatory. Given that the magnetic latitude of the Kakioka observatory is about 27.8°, this research can illuminate the response of the electric fields (and GICs) to the geomagnetic disturbances at low latitudes where Woodroffe et al. (2016) did not discussed well. In this paper, we focused on the first three types of the variations, that is, the SSCs/SIs, the main phase of storms, and the bay disturbances. We excluded the variation associated with the SFEs because the amplitude associated with the SFEs is relatively small. Knowing $\Delta E_x$ and $\Delta E_y$, we calculated the GICs flowing at the substations in Japan with the aid of Equation 1 and the parameters summarized in Table 1.

2. Data
2.1. Geoelectric Field Data
We used 1-min resolution data of the geoelectric field observed at Kakioka Magnetic Observatory (36.23°N, 140.19°E, 27.8° geomagnetic latitude). The $x$- and $y$-components refer to the geographical north and east components, respectively. The technical description of the measurement of the geoelectric field is given by Fujii et al. (2015). It is confirmed that the horizontal components of the geoelectric field are induced by variations in the geomagnetic field at periods below 10$^5$ s, which enables us to utilize the geoelectric field data as a proxy of GICs. The geoelectric field at periods below 10$^3$ s is suffered from artificial noise, but the coherence between the geoelectric field and the geomagnetic field is shown to increase for geomagnetic storms (Fujii et al., 2015). We focus on the variations with a period $<10^3$ s, and believe that the observed electric field is induced by geomagnetic variations.

2.2. SSCs and SIs
We used 218 SSCs/SIs identified by Kakioka Magnetic Observatory (http://www.kakioka-jma.go.jp) from 1996 to 2004 (around the maximum of the 23rd solar cycle). We excluded five SSCs/SIs for which the geoelectric data
2.3. Magnetic Storms (Storm Main Phase)

We focused on intense magnetic storms having minimum $D_{st}$ index being less than $-100$ nT from 1996 to 2004, which were collected by Kataoka and Miyoshi (2006). Only the magnetic storms driven by coronal mass ejections are used in this study because clear SSCs/SIs preceded the main storm. We excluded the 13 magnetic storms for which the duration from the SSCs/SIs to the end of the main phase is longer than 24 hr, or the geoelectric field data is missing. The original list (Kataoka & Miyoshi, 2006) provides the storm maximum in terms of 1-hr $D_{st}$ index. We redefine the storm maximum at which the 1-min SYM-H index reached the minimum, and referred it to as $ep_2$. A list of $ep_2$ and the minimum SYM-H are summarized in Supporting Information S1 (SI2). The minimum SYM-H ranges from $-490$ to $-106$ nT.

We have repeated the same analyses for moderate magnetic storms ($-100$ nT < minimum $D_{st}$ ≤ $-50$ nT) from 1996 to 2008 (Echer et al., 2011, 2013). However, the geoelectric field disturbances are smaller than those for the intense magnetic storms, and the qualitative results are almost the same as those for the intense magnetic storms. Thus, the results for the moderate magnetic storms are not shown here.

2.4. Bay Disturbance

We used a list of the bay disturbances identified by Kakioka Magnetic Observatory (http://www.kakioka-jma.go.jp). In accordance with the amplitude, three classes are defined in the identification of the bays, A, B, and C. We used all the classes, that is, the amplitudes of it exceeds 10 nT for quiet times and 25 nT for active times. In total, 325 bay disturbances that took place from 1996 to 2004 were used to analyze, which are listed in Table SI3 in Supporting Information S1. The beginning of bay disturbances is referred to as the epoch time denoted by $ep_3$.

2.5. Example of Geoelectric Field Variations

Figure 1 shows an example of the $y$-component of the geoelectric field $E_y$ and $H$ observed at Kakioka on 18–20 October 1998. During this interval, an SSC, an intense magnetic storm and a bay disturbance occurred. At 1951 UT on 18 October 1998, $H$ started to increase rapidly, corresponding to an SSC. This moment is regarded as $ep_1$. At the same time, $E_y$ started a negative excursion. Then, the main phase of the storm began at ~04 UT on 19 October 1998 as identified from a decrease in $H$. A negative SI-like disturbance took place during the storm main phase, along with $H$ decreased by more than 100 nT (This event has been identified as a SI according to the latest data provided by Kakioka Magnetic Observatory). The SYM-H reached the minimum value at 1,522 UT,
which is regarded as ep₂. During the storm main phase, a positive bay disturbance commenced at 1,320 UT on 19 October 1998, which is regarded as ep₃. The bay disturbance brought a great impact on the variations of the geoelectric field, $E_y$ shows a negative excursion with an approximate amplitude of $\sim 150$ mV/km correspondingly. Later, we evaluate the contribution from the storm-time ring current to GIE. For this particular magnetic storm, we excluded the influence on the variations brought by SI disturbance (0455 UT on 19 October 1998) and the bay disturbance (1,320 UT on 19 October 1998) through a smoothing process (explained in detail in Section 3.2), and obtained the maximum amplitude of geoelectric field disturbance $E_y$ at 1,110 UT on 19 October 1998.

3. Results

3.1. SSCs and SIs

We calculated the disturbances of the magnetic field $\Delta B_1$ and the electric field $\Delta E_1$ as

$$\Delta B_1(t) \equiv B(t) - B(\text{ep1}),$$

$$\Delta E_1(t) \equiv E(t) - E(\text{ep1}).$$

Figure 2 shows the superposed epoch averages of $\Delta B_1$ and $\Delta E_1$ for the epoch time ep₁. On average, $\Delta B_{1,x}$ shows a rapid increase after ep₁. This is a typical tendency for the geomagnetic disturbances associated with SSCs/SIs. Negative changes in $\Delta B_{1,x}$ are also included in this figure, which are likely associated with a sudden decrease in the solar wind dynamic pressure (Nishida & Jacobs, 1962; Takeuchi et al., 2000). The averaged $\Delta B_{1,y}$ also shows an increase, but the magnitude is smaller than that of $\Delta B_{1,x}$. $\Delta E_{1,x}$ and $\Delta E_{1,y}$ show negative excursions. The averaged $\Delta E_{1,x}$ reaches $-65$ mV/km, whereas that of $\Delta E_{1,y}$ reaches $-11$ mV/km about 3 min after ep₁. At Kakioka, the northward magnetic disturbances are known to cause the induced electric field primarily in the westward direction (Love & Swidinsky, 2014).

We sorted $\Delta E_{1,y}$ in accordance with magnetic local time (MLT) sectors, 00–06, 06–12, 12–18, and 18–24 MLTs. The results are shown in Figure 3. $\Delta E_{1,y}$ shows similar variations after ep₁ for all the MLT sectors. The maximum amplitudes of averaged $\Delta E_{1,y}$ are about 77, 36, 57, and 80 mV/km in 00–06, 06–12, 12–18, and 18–24 MLTs, respectively. The maximum amplitudes are slightly larger on the nightside than those on the dayside. This is probably caused by the contribution from the field-aligned current and the ionospheric current that developed on the nightside during the SSCs and SIs (Araki et al., 2006).

The relationship between $\Delta E_{1,x}$ and $\Delta E_{1,y}$ at the maximum $|\Delta E_1|$ for the period from ep₁ to ep₁+15 min are shown in the left panel of Figure 4. $\Delta E_{1,x}$ and $\Delta E_{1,y}$ are highly correlated with each other. The dependence of $\Delta E_{1,x}$ and $\Delta E_{1,y}$ on $|\Delta H|$ is shown in the middle and the right panels of Figure 4. At a glance, linear relationship can be reasonably identified. We obtained the following regression lines without intercepts,

$$\Delta E_{1,x}(\text{mV/km}) = -(0.73 \pm 0.05)|\Delta H| (\text{nT}),$$

$$\Delta E_{1,y}(\text{mV/km}) = -(4.31 \pm 0.12)|\Delta H| (\text{nT}).$$

The correlation coefficients are $-0.68$ and $-0.97$ for $\Delta E_{1,x}$ and $\Delta E_{1,y}$, respectively. The numerical figures following the symbol of ± represent the upper and lower limits of the 95% confidence level of the slope. The physical meaning of the linear relationship will be discussed below. Of course, the empirical equation is crude in comparison with a convolution method (Love & Swidinsky, 2014). The usefulness and the application to GICs will also be discussed below.

3.2. Magnetic Storms (Storm Main Phase)

Figure 5 shows the result of the superposed epoch analysis of $\Delta B_1$ and $\Delta E_1$ for the epoch time ep₂. ep₂ corresponds to the moment when the SYM-H index reached a minimum, that can be regarded as a storm maximum. At a glance, the averaged $\Delta B_{1,x}$ decreases during the storm main phase (before ep₂), and increases during the storm recovery phase (after ep₂). These changes are well consistent with those in the SYM-H index. $\Delta E_{1,y}$ increases
Figure 2. Superposed epoch averages of (a) $\Delta B_{\text{x},x}$ (positive northward), (b) $\Delta B_{\text{y},x}$ (positive eastward), (c) $\Delta E_{\text{x},x}$ (positive northward), and (d) $\Delta E_{\text{y},x}$ (positive eastward). The red lines indicate the averaged values and the gray regions indicate standard deviations. $\text{ep}_{1}$ refers the moment at which storm sudden commencements/sudden impulses begin.
during the storm main phase, and decreases during the recovery phase. It reaches the maximum value of 84 mV/km at ep2, at which the rate of change in $\Delta B_{1,x}$ is almost zero. After ep2, the averaged $\Delta E_{1,y}$ starts to decrease and remains positive for a few hours, while the averaged $\Delta B_{1,x}$ monotonically increases. This can be explained by the cumulative effect of geomagnetic variations, according to the convolution theory suggested by Cagniard (1953). That is, the peak of GIE tends to appear where $\partial B/\partial t$ changes the sign. We have not found significant dependence of $\Delta E_{1}$ on MLT (data not shown).

Figure 6 is the same as Figure 4 except for storm main phase. We removed short-lived spikes and SI-like disturbances by applying a moving median method, and took the maximum amplitude of $|\Delta E_{1}|$ for the period from ep1 + 15 min to ep2. Again, fairly well correlation between $\Delta E_{1,y}$ and $\Delta H$, and that between $\Delta E_{1,x}$ and $\Delta H$ are found. From the linear regression analysis, we obtained the following equations.

\[
\Delta E_{1,x}\text{(mV/km)} = -(0.11 \pm 0.01) \Delta H\text{(nT)},
\]
\[
\Delta E_{1,y}\text{(mV/km)} = -(0.85 \pm 0.11) \Delta H\text{(nT)}.
\]

(4)

Figure 3. Superposed epoch averages of $\Delta E_{1,y}$ for the storm sudden commencements/sudden impulses for four magnetic local time sectors.

Figure 4. Relationship between (left) $\Delta E_{1,y}$ and $\Delta E_{1,x}$; relationship between (middle) $\Delta E_{1,y}$ and $\Delta H$; and (right) $\Delta E_{1,x}$ and $\Delta H$ at the maximum of $|\Delta E_{1}|$ for the storm sudden commencements/sudden impulses.
The correlation coefficients are \(-0.64\) and \(-0.76\) for \(\Delta E_{1,x}\) and \(\Delta E_{1,y}\), respectively. The physical meaning of Equation 4 and the application will be discussed below.

### 3.3. Bay Disturbances

Figure 7 shows the results of the superposed epoch averages of the GIEs for the bay disturbances. The disturbances of the magnetic field \(\Delta B_3\) and the electric field \(\Delta E_3\) for the epoch time \(\text{ep}_3\) were obtained by

\[
\Delta B_3(t) \equiv B(t) - B(\text{ep}_3),
\]

\[
\Delta E_3(t) \equiv E(t) - E(\text{ep}_3).
\]

where \(\text{ep}_3\) refers to the moment at which the bay disturbances begin. \(\Delta B_{3,x}\) shows a rapid increase, and reaches a maximum about 40 min after \(\text{ep}_3\), which is consistent with a typical variation of the positive bay (Akasofu & Meng, 1969; McPherron et al., 1973; Meng & Akasofu, 1969). \(\Delta E_{3,x}\) and \(\Delta E_{3,y}\) show negative excursions, and reached minima about 25 min after the expansion onset.

Figure 8 shows the relationship between \(\Delta E_3\) and \(\Delta H\) at the moment when the amplitude of \(\Delta E_3\) is maximized for the period from \(\text{ep}_3\) and \(\text{ep}_3 + 1\) hr. We obtained the following equations for the bay disturbances.

\[
\Delta E_{3,x}(\text{mV/km}) = -(0.34 \pm 0.01)\Delta H(\text{nT}),
\]

\[
\Delta E_{3,y}(\text{mV/km}) = -(2.18 \pm 0.09)\Delta H(\text{nT}).
\]

The correlation coefficients are \(-0.83\) and \(-0.83\) for \(\Delta E_{1,x}\) and \(\Delta E_{1,y}\), respectively.

### 3.4. Occurrence Distribution of GIE

Figure 9 shows occurrence distributions for the SSC/SIs, the storm main phase, and the bay disturbances during 1996–2004. For the SSCs/SIs, we took the maximum \(\Delta E_1\) for the period from \(\text{ep}_1\) to \(\text{ep}_1 + 15\) min. The largest value reaches 617 mV/km, which was recorded on 15 July 2000. For the storm main phase, the largest value reaches 210 mV/km on 20 November 2003. For the bay disturbances, the largest amplitude is 325 mV/km at 0946 UT on 10 November 2004. Note again that these values are all the largest ones for each event referred above. To illuminate the underlying tendency of GIE distribution caused by the three types of the geomagnetic disturbances in the solar cycle, we performed the generalized extreme value distribution (GEVD; Kotz & Nadarajah, 2000). The probability density function for the GEVD with a location parameter \(\mu\), a scale parameter \(\sigma\), and a shape parameter \(k\) (\(k\neq 0\)) is given by

\[
y = f(x|\mu, \sigma) = \left(\frac{1}{\sigma}\right) \exp\left(-\left(1 + k\frac{x - \mu}{\sigma}\right)^{\frac{1}{k}}\right) \left(1 + k\frac{x - \mu}{\sigma}\right)^{-1 - \frac{1}{k}}
\]

for

\[1 + k\frac{x - \mu}{\sigma} > 0.\]
The results are shown by the red curves in Figure 9. We set the binning width of bars as 25 mV/km to avoid the statistical noise of the distribution. Parameters of the equation for three types of disturbances are presented in Figure 9.

We predicted 10- and 100-year values, which may help unveil the potential risk of GIC problems in the power grid in Japan. We obtained the return values in the GEVD by using the following equation:

$$x_T = \mu - \frac{\sigma}{k} \left(1 - \left[-\log \left(1 - \frac{1}{T}\right)\right]^{-k}\right)$$

for $$k \neq 0$$

(8)

where $$x_T$$ is called a return value, which is defined as a value that is expected to be equaled or exceeded on average once every interval of time $$T$$ (with a probability of $$1/T$$). $$T$$ refers to a return period. Following Woodroffe et al. (2016), we estimated 10- and 100-year $$|\Delta E|$$ for the SSCs/SIs, the main phase of storms, and the bay disturbances. The results are presented in Table 2. The 10-year values of $$|\Delta E|$$ are 241.7, 204.9, and 177.4 mV/km for the SSCs/SIs, the main phase of storms, and the bay disturbances, respectively. The 100-year values are 612.3, 442.3, and 455.9 mV/km, respectively, but they may have some uncertainty because we used data obtained in 1996–2004. We will discuss these values later.

The largest GIE associated with the SSCs/SIs is 617 mV/km ($$\Delta E_x$$ of −125.7 mV/km and $$\Delta E_y$$ of −603.9 mV/km) in 1996–2004, which is nearly equal to the 100-year value as summarized in Table 2. For the storm main phase, the largest GIE in 1996–2004 is 210 mV/km ($$\Delta E_x$$ of 25.2 mV/km and $$\Delta E_y$$ of 208.9 mV/km), which is close to

![Figure 6](image-url)

**Figure 6.** Same as Figure 4 except for the moment when the maximum value of $$|\Delta E|$$ took place for storm main and recovery phases.

![Figure 7](image-url)

**Figure 7.** Superposed epoch averages of (a) $$\Delta B_x$$ and (b) $$\Delta E_x$$ for the bay disturbances. ep3 refers to the moment at which the bay disturbances begin.
the 10-year value. For the bay disturbances, the largest GIE is 325 mV/km ($\Delta E_x$ of $-51.6$ mV/km and $\Delta E_y$ of $-321.2$ mV/km), which is close to the 10-year value.

### 3.5. Validation of the Empirical Equations

We performed a case study to validate the applicability of the empirical equations. Figure 10 summarizes $\Delta H$, $\Delta E_x$, $\Delta E_y$, and $|\Delta E|$ observed at Kakioka for the magnetic storm of 20 April 2020. The SSC was recorded at 0230 UT on 20 April 2020, with the amplitude $\Delta H$ of 12 nT. Substituting $\Delta H$ of 12 nT into Equation 3, we obtained $\Delta E_x$ and $\Delta E_y$ to be $[-9, -8]$ mV/km and $[-53, -50]$ mV/km, respectively. The numerical figures in the square brackets indicate the values obtained by the upper and lower limits of the 95% confidence levels of the slope of Equation 3. These amplitudes are fairly consistent, but slightly larger than the observed ones shown in the second and third panels of Figure 10. Substituting $\Delta E_x$ and $\Delta E_y$ to Equation 1, with the coefficients summarize in Table 1, we obtained GICs at SFS to be $[-3.2, -3.1]$ A, which is about ∼1.5 times larger than the observed GIC of $-2$ A in magnitude as shown in Figure 2e in Ebihara et al. (2021). During the SSC, the maximum amplitude of the GIC at STB and SFJ are less than 1 A, which also makes difficult to compare with the observations due to the offset values.

As for the storm main phase, we performed the same manner presented in Section 3.2. First, we removed short-lived spikes by applying a moving median method to extract the contribution from the ring current that varies relatively slowly. The smoothed values are indicated by the red lines in Figure 10. The smoothed values show plateaus, but we confirmed that they are not glitch in the calculation. The maximum value of the smoothed $|\Delta E|$ is found to take place at 1013 UT on 20 April 2020. At this moment, $\Delta H$ was $-73$ nT. Substituting $\Delta H$ of $-73$ nT into Equation 4, we obtained $\Delta E_{1,x}$ and $\Delta E_{1,y}$ to be $[7, 9]$ mV/km and $[54, 70]$ mV/km, respectively. With Equation 1, we obtained GIC for SFS to be ∼$[1.8, 2.6]$ A. At this moment, the GIC observed at SFS is ∼2 A as shown in Figure 2e in Ebihara et al. (2021), which is consistent with this estimate.

Next, we focus on the magnetic storm that took place on 13–14 March 1989, which is the largest one in terms of the minimum $Dst$ value since 1957. During the magnetic storm, the minimum $\Delta H$ is $\approx-597$ nT (which is the averaged value between 0018 and 0028 UT on 14 March 1989) at Kakioka. Substituting $\Delta H$ of $-597$ nT into Equations 4 and 1, we obtained the GIC values at SFS, STB and SFJ to be $[20, 28], [-5, -6]$, and $[0, 2]$ A, respectively. The maximum GIC values obtained based on the convolution method are $\approx11, -3$, and $-2$ A, respectively, at 0025 UT on 14 March 1989 (Ebihara et al., 2021). Note that the GICs were not measured at SFS, STB, and SFJ during the magnetic storm. For SFS and STB, the amplitude of the estimated GICs are about two times larger than that obtained by the convolution method. The GICs at SFJ are not well reproduced. One of the plausible reasons is that the GICs at SFJ is more sensitive to $\Delta E_y$, likely depending on $\Delta D$ (geomagnetically east-west component of the magnetic disturbance), rather than $\Delta H$. Inhomogeneous ground conductivity and the network topology can also make the difference (Nakamura et al., 2018).

We recognize that the empirical Equations 3, 4 and 6 give estimates that are less accurate than those obtained by a convolution method (Love & Swidinsky, 2014). For the magnetic storm of 20 April 2020, the estimated
GICs are consistent with the observed ones. For the magnetic storm of 13–14 March 1989, the estimated GICs are about three times larger in magnitude than obtained by the convolution method. The temporal variations of the SSCs/SIs and the storm main phase vary with magnetic storms, and the estimated GICs do not necessarily match the precise values. However, we believe that these empirical equations are useful for evaluating extreme values of GIEs and GICs for which temporal variations of the geomagnetic field are not provided.

**Figure 9.** Histograms of the number of samples as a function of $|\Delta E|$, distribution and generalized extreme value distribution fitting results for (a) the storm sudden commencements/sudden impulses, (b) the storm main phase, and (c) the bay disturbances. The numerical figures above the bars indicate the number of occurrences. The left axis shows the probability density.

| Geomagnetic activity | 10-Year $|\Delta E|$ (mV/km) | 100-Year $|\Delta E|$ (mV/km) |
|----------------------|------------------------------|-------------------------------|
| SSCs/SIs             | 241.7                        | 612.3                         |
| Main phase of storms | 204.9                        | 442.3                         |
| Bay disturbances     | 177.4                        | 455.9                         |
4. Discussion and Summary

For the SSCs/SIs, $\Delta E_{1,x}$ and $\Delta E_{1,y}$ are shown to be correlated fairly well with $\Delta H$. This might be consistent with the statistical studies showing that $\Delta H/\Delta T$ is well correlated with $\Delta H$, where $\Delta T$ is the rise time of SSCs/SIs (Araki et al., 2004). Similar tendency is also reported by Mayaud (1975). Araki et al. (2004) pointed out that for the large amplitude of SSCs/SIs, $\Delta H$ increases rapidly. Wang et al. (2006) showed that the rise time of SSCs decreases with increasing the solar wind speed. The amplitude of the $\Delta H$ associated with SSCs/SIs is also known to be proportional to the square root of the solar wind dynamic pressure, that is, being proportional to the solar wind speed (Ogilvie et al., 1968; Siscoe et al., 1968). The global MHD simulation also supports these observational facts (Kubota et al., 2015). These observational and simulation results can explain the fact that $\Delta H/\Delta T$ is well correlated with $\Delta H$. The physical mechanism that determines the linear relationship is not clear, and is expected to be complicated because of the transient phenomena involving the magnetosphere-ionosphere coupling processes (Araki, 1994; Piersanti & Villante, 2016) as well as frequency dependent response of ground (Fujii et al., 2015). If $\Delta E$ is simply proportional to $\partial B/\partial t$, $\Delta E$ would also be proportional to $\Delta H/\Delta T$. Of course, according to the convolution theory (Cagniard, 1953; Love & Swidinsky, 2014), $\Delta E$ is not necessarily proportional to $\partial B/\partial t$.

Yokoyama and Kamide (1997) investigated more than 300 magnetic storms, and found that the duration of the storm main phase ($\Delta T$) does not increase linearly with the peak $Dst$ value ($\Delta Dst$). However, $\Delta Dst/\Delta T$ does intend to increase with $\Delta Dst$, that is, large magnetic storms develop rapidly. This might explain, in part, the quasi-linear relationship between $\Delta E$ and $\Delta H$.

McPherron and Chu (2018) calculated the probability density of the duration of the bay disturbances (magnetic positive bays) that took place from 1981 to 2012. The peak of the probability density ranges from ~32 for small bays to ~45 min for large bays. Their results indicate that the duration does not depend significantly on the size of the bays. If so, the amplitude of $\partial B/\partial t$ would be roughly proportional to the maximum value of $\Delta H$. 

Figure 10. From the top, $\Delta H$, $\Delta E_x$, $\Delta E_y$, and $|\Delta E|$ for the magnetic storm on 20 April 2020. The vertical line indicates the moment when the smoothed $|\Delta E|$ reaches the maximum during the storm main phase. The red lines indicate the values smoothed by the moving median method.
On the basis of the magnetic field data obtained between 1981 and 2011, Woodroffe et al. (2016) showed that the median values of the electric field calculated from the magnetic field are ~72, ~166, and ~245 mV/km at the magnetic latitude of 20°–30° for the ranges –200 < Dst ≤ –100, –300 < Dst ≤ –200, and Dst ≤ –300 nT, respectively. The median values of ΔEl observed at Kakioka (27.8° magnetic latitude) for the range Dst < –100 nT is 80 mV/km for the SSCs/SIs and 78 mV/km for the storm main phase as shown in Figure 9. These median values are reasonable in comparison with those obtained by Woodroffe et al. (2016). It is interesting to note that the median value for the SSCs/SIs is close to that for the storm main phase. This implies that the SSCs/SIs and the storm main phase are equally of importance in the electric field. Although Woodroffe et al. (2016) did not distinguish the SSCs/SIs and the storm main phase, their results are, of course, valid in the evaluation of the median values for the magnetic storms (including SSCs/SIs).

It is of importance to estimate the GIC values for extreme events. For example, the largest amplitude of the ΔH disturbance associated with the SSCs/SIs is >273 nT at Kakioka, recorded on 24 March 1940 (Araki, 2014). Substituting ΔH of 273 nT to Equation 3, we obtained ΔE1,Δ and ΔE1,1 to be [−213, −186] and [−1,209, −1,144] mV/km, respectively. The GICs that could flow at SFS, STB, and SFJ are estimated to be [−55, −53], [12, 12], and [7, 13] A, respectively.

Kataoka (2013) showed the probability of extreme storm-time disturbances of ΔH at Kakioka. Moriña et al. (2019) also performed statistical analysis of the Dst index, and provided the probability. For example, the occurrence frequency for the threshold level of –800 nT is 1.37 per 1,000 years. Their occurrence probability does not provide the temporal variation of ΔH. However, using Equations 3, 4 and 6, we can estimate GIEs and GICs without knowing the temporal variation, which will be useful for tolerance evaluation of electric facilities of the power grid. Vasyliunas (2011) theoretically estimated the upper limit of the storm-time ring current, and suggested the minimum Dst value of −2,500 nT. It would be reasonable to regard ΔDst = ΔH at Kakioka for the purpose of evaluating the extreme value as a zeroth order approximation because Kakioka is one of the Dst stations. Substituting ΔH of −2,500 nT to Equation 4, we obtained ΔE1,Δ and ΔE1,1 to be [250, 300] and [1,850, 2,400] mV/km, respectively. With Equation 1, we calculated GICs flowing at SFS, STB and SFJ to be [88, 117], [−20, −26], and [2, 10] A, respectively.

One of the most severe magnetic storms ever observed is the Carrington storm that occurred in 2 September 1859 (Siscoe et al., 2006; Tsurutani, 2003). At Bombay, the minimum ΔH was recorded to be ≈−1,600 nT (Tsurutani, 2003). Following Sugiura (1991, WDC Kyoto, http://wdc.kugi.kyoto-u.ac.jp/dstdir/dst2/onDstindex.html), we corrected the magnetic record at Colaba by removing the possible contribution from the magnetic latitude effect. The corrected ΔH for Kakioka is ≈−1,450 nT (=−1,600 nT × cos λK/cos λC, where λK and λC are the magnetic latitudes at Kakioka (≈27°) and that at Colaba (≈10°), respectively). Substituting ΔH of −1,450 nT into Equations 4 and 1, GICs flowing at SFS, STB, and SFJ are estimated to be [51, 67], [−11, −15], and [1, 6] A, respectively. Ebihara et al. (2021) used the time-series data of the magnetic field observed at Bombay on 2 September 1859, and estimated GIEs at Kakioka by taking convolution of the magnetic field. With Equation 1, Ebihara et al. (2021) obtained the maximum GIC values to be [59, 119], [−27, −13], and [−46, 8] A at SFS, STB, and SFJ, respectively.

According to the Kakioka observatory, the maximum amplitude of the bay disturbances is ~100 nT at Kakioka since 1,957. Substituting ΔH of 100 nT into Equations 6 and 1, we estimated GICs flowing at SFS, STB and SFJ to be [−11, −10], [2.4, 2.2], and [0.7, 0.9] A, respectively.

SIs and bay disturbances often occur during the magnetic storms as shown in Figure 1. At Kakioka, ΔE1,Δ tends to be positive during the storm main phase, while it decreases to negative values during the storm recovery phase as shown in Figure 5. On average, both the SSCs/SIs and the bay disturbances give rise to negative excursions of ΔE1,Δ as shown in Figures 3 and 7. It is expected from these results that the magnitude of ΔE1,Δ would be amplified (negative deflection) when the SSCs/SIs and/or the bay disturbances occur during the storm recovery phase. An exception is a negative SI, which is caused by the sudden decrease in the solar wind dynamic pressure. When the negative SI occurs during the storm main phase, the amplitude of ΔE1,Δ is also amplified (positive deflection) as shown in Figure 1. On average, E1,Δ shows a broad, positive excursion from ~04 UT to ~13 UT on 19 October 1998. This interval is a part of the main phase of the storm in October 1998. A negative SI, occurred at ~05 UT on 19 October, resulting in the further increase in E1,Δ.
It is possible that extreme SIs occur during an extreme magnetic storm. Tsurutani and Lakhina (2014) pointed out that if a second interplanetary shock arrives at Earth while a magnetic storm is ongoing, this type of the solar wind condition is geoeffective. The large-amplitude GICs, as high as 129 A, were recorded in the Japanese power grid on 30 October 2003 (METI, 2015). Ebihara et al. (2021) suggested that the large-amplitude GICs recorded on 30 October 2003 could result from the arrival of an interplanetary shock in the course of the recovery phase of the intense magnetic storm of 28–30 October 2003, known as the Halloween event. It is also possible that bay disturbances occur during an extreme magnetic storm. Hajra et al. (2016) showed that extreme substorms (super-substorms) with minimum SML index being less than −2,500 nT often occur during the storm main and recovery phases. The SML index is an extension of the AL index, representing the magnitude of the westward ionospheric current at high latitudes (Newell & Gjerloev, 2011). The amplitude of the bay disturbances is not necessarily correlated with the amplitude of the SML index for the supersubstorms since the mid-latitude bay disturbances are primarily caused by the field-aligned currents whereas the decrease in the SML index is primarily caused by the ionospheric Hall current depending on the ionospheric electric field and the conductivity. Further studies are needed to investigate the relationship between the magnetic storms and the substorms in terms of GICs. To assess the worst values of GICs flowing at low and mid latitudes, one should take into consideration the combination among the magnetic storms, the SIs and the bay disturbances.

According to the documents published by the North American Electric Reliability Corporation (NERC, 2016), the effective GIC of 75 A (225 A per 3 phases) is set to be a conservative screening criterion for thermal impact assessments of transformers. These GICs estimated above are probably less than the screening criterion for these particular substations, that is, SFS, STB, and SFJ. If GIC data is available for the other substations and generators, the same calculation is applicable to estimate the GICs for extreme events. However, it is almost unrealistic to measure the GICs at all the substations and generators in a nation. An alternative way is to calculate numerically the GIE distribution in Japan (Püthe et al., 2014; Fujita et al., 2018; Nakamura et al., 2018), and to solve the equation of continuity of the current flowing in the grid (Lehtinen & Pirjola, 1985). Eventually, the coefficients $a$, $b$, and $c$ of Equation 1 would be obtained for all the facilities of the power grid. If the solar wind conditions are reasonably predicted by simulations (e.g., Odstrcil, 2003; Shiota & Kataoka, 2016) in a real time manner, the maximum $|\Delta Dst|$ values would be calculated immediately with the aid of an empirical model (e.g., Burton et al., 1975). Substituting the estimated $|\Delta Dst|$ values to Equations 3 and 4, one can estimate immediately the maximum GIC values at the substations/generators at which the coefficients $a$, $b$, and $c$ of Equation 1 are known. We will verify the validity of this scheme for the real-time prediction of GICs at mid and low latitudes.

Data Availability Statement
The geoelectric field data, the list of SSCs/SIs, and the bay disturbance list are available at http://www.kakio-ka-jma.go.jp. The SYM-H index data were obtained from the WDC for geomagnetism, Kyoto, and are available at http://wdc.kugi.kyoto-u.ac.jp/aeasy.

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