Electromagnetic induction responses to geomagnetic disturbances at low-and-mid-latitudes

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Abstract. The geomagnetically induced current (GIC) is one of the most widely recognized phenomena caused by geomagnetic disturbances. Realistic predictions of magnetic field fluctuations may be used to evaluate the induction of electric fields to ground surfaces, and thus to estimate the occurrence of GICs. Although many GICs occur at high latitudes, they are now being studied at low and mid-latitudes as well. The purpose of this research was to understand the dynamics, observation, and prediction in Japan for GICs occurring at the low and mid-latitudes. In this study, the influence of geomagnetic field variations on Earth’s electric field was examined. The magnetic field and the electric field components of 3 observation points for 1 year in 2015 are visually examined, and the characteristics of the fluctuations of the magnetic field and the surface electrical field were also analysed.

1. Introduction

Due to space weather phenomena such as magnetic storms and substorms, Earth’s magnetic field changes daily. These phenomena are known to have many influences on our lives, including one such phenomenon, the geomagnetically induced current (GIC). GIC is the current induced in the ground by changes in the geomagnetically induced electric field (GIE) due to geomagnetic disturbance. If GIC flows into a transmission line, the supply of electricity will be hindered; if it flows into an underground pipeline, it will advance the corrosion of the pipe.

Japan is considered to have a magnetic latitude that is lower than the geographical latitude, and it is difficult for the country to be affected by GIC [Watari et al. 2015]. However, in recent years research to observe and predict GICs has nonetheless advanced in Japan.

This study aimed to establish a predictive method of GIE, which is the electromotive force of GIC, at low and mid-latitudes, especially in Japan. As an initial stage of this research, it is emphasized here that the clarification of the relationship between the geomagnetic field and Earth’s electric field, especially observational values.
2. Data

Earth’s geomagnetic and electric fields are observed by the Japan Meteorological Agency in Masumitsu (MMB), Kakioka (KAK), and Kanoya (KNY), Japan. These observational values are made available on the web [http://www.kakioka-jma.go.jp/obsdata/metadata/ja]. This research uses that data from January 1, 2015 to December 31, 2015; and uses northward+ (H), eastward+ (D), downward+ (Z) of the magnetic field, and northward+ (Ex), eastward+ (Ey) of the electric field. The difference between the median and the raw data values is denoted as \( d \).

![Figure 1. The observation points, Memanbetsu(MMB), Kakioka(KAK), and Kanoya(KNY). All of these locations observe Earth's geomagnetic field and electric field.](image)

3. Analyses

3.1. Development of GIE during aurora substorms onset in MMB

To analyze the origination directions of substorms in MMB, this research used 1-sec geomagnetic field data, 1-sec electric field data, and the auroral electrojet (AE) index (WDC).

First, all daily data from 2015 were examined, and counted the substorm events using the AE index. Among them, those events were limited conditions at MMB to 18-06 LT (09-21UT) because substorms are a phenomenon of the night sky wherein clear changes in Earth's geomagnetic and electric fields are observed. There are 139 events were listed up.

Secondly, because the current path with the substorm has a local time dependence, events were classified as 09-12UT, 12-15UT, 15-18UT, or 18-21 UT. Focusing on the direction of electric field origination for any given substorm, they were classified as northeast (NE), northwest (NW), southeast (SE), and southwest (SW).

Table 1 shows the number of events classified by the origination direction and the time of occurrence. From this table, it can be seen that the NE electric field easily develops in or near to evening time; on the contrary, the SW electric field mainly develops in the times in or near the morning.
Figure 2. Example of the classification by time and component of events as originating in the northeast (NE), presented as a peak in the difference between the median and raw northward+ and eastward+ component of the electric field, or southwest (SW), presented as a trough in the difference between the median and raw northward-(southward+) and eastward-(westward+) component of the electric field.

Table 1. Number of events classified by start time and component type. Black shading indicates places where more than 10 events could be confirmed.

| Time (UT)  | NE | NW | SE | SW |
|------------|----|----|----|----|
| 9-12UT (18-21LT) | 48 | 0  | 0  | 2  |
| 12-15UT (21-24LT) | 21 | 0  | 0  | 21 |
| 15-18UT (24-3LT) | 1  | 0  | 1  | 27 |
| 18-21UT (3-6LT) | 2  | 0  | 0  | 16 |

3.2. Development of GIE during the magnetic storm

Figure 3 shows the observations of the magnetic and the electric fields for a magnetic storm (St. Patrick’s), which occurred in March of 2015. During this magnetic storm, the correlation between Earth's magnetic field and electric field was investigated.

The correlation coefficient was first calculated for each of the three magnetic field components, as well as for the two electric field components (Raw). Second, in order to remove waves of a relatively long period, such as the daily fluctuations of the magnetic field, the correlation coefficient was also calculated using a high-pass filter with a period of 30 minutes (High-pass).

Table 2. Raw and high-pass correlation coefficient of each component on Mar 17, 2015 at MMB, KAK, and KNY. Larger absolute values are shown in gray.

|          | MMB Raw | MMB High-pass | KAK Raw | KAK High-pass | KNY Raw | KNY High-pass |
|----------|---------|---------------|---------|---------------|---------|---------------|
| dH – dEx | -0.30   | -0.57         | -0.29   | -0.62         | -0.19   | -0.27         |
| dH – dEy | -0.36   | -0.72         | -0.43   | -0.68         | -0.40   | -0.71         |
| dD – dEx | 0.37    | 0.78          | 0.03    | 0.03          | 0.52    | 0.21          |
| dD – dEy | 0.30    | 0.70          | -0.16   | -0.18         | -0.19   | -0.24         |
| dZ – dEx | -0.28   | -0.87         | -0.62   | -0.62         | 0.13    | -0.17         |
| dZ – dEy | -0.21   | -0.70         | -0.58   | -0.64         | -0.54   | -0.69         |

(R: Correlation coefficient)
In Table 2, the correlation is better in most cases when magnetic field fluctuations on the 30-minute scale are excluded. This finding supports the idea that the electric field responds to the short-term magnetic field fluctuations more so than the long-term fluctuations.

![Graph of geophysical data](image)

**Figure 3.** The difference between the median and raw values of the northward+ ($dH$), eastward+ ($dD$), and downward+ ($dZ$) components of the geomagnetic field (upper row), and of the northward+ ($dEx$) and eastward+ ($dEy$) components of the electric field (bottom row) at Memanbetsu (MMB). There is a tendency for the electric field to develop more easily from magnetic field fluctuations on the scale of several minutes after 13 UT, rather than from fluctuations of the magnetic field on the scale of several hours near 5 UT.

3.3. *Development of GIE by geomagnetic pulsation in MMB.*

Geomagnetic pulsation is a known magnetic disturbance phenomenon during the daytime. The daytime geomagnetic pulsation is a periodic fluctuation of 0.2 to 100 seconds.

The pulsation in the electric field during the daytime can be seen in Figure 4. Since this pulsation occurs at the same time as the pulsation of the magnetic field, this suggests that the fluctuation of the magnetic field may cause the electric field pulsation. Currently, proposed GIE generation models are mostly focused on ionospheric currents or equatorial electrojets (EEJs) originating from general GIE. However, due to fluctuation of geomagnetic field itself, the GIE may not depend on large current systems, which also suggests that the electric field may develop.
4. Discussion

The time dependency of the electric field origination direction during substorms is caused by the current system in the sky (Table 1). In the skies of Japan, at the time of substorm occurrence, the field-aligned current (FAC) is mostly toward the south in the evening, and many occur in the northward direction in the morning. Even from the limited number of electric field observations, it is clear that there are many forces that oppose the FAC. However, despite the fact that the FAC is seen from 12-15 UT due to the evening darkness, origination of the same number of events from the northeast and southwest indicates that the direction of electric field origination is determined by multiple factors, not only FAC.

That the electric field is more likely to develop with shorter variations than the long-time fluctuations, such as the daily fluctuation considered in section 3.2, can be explained by Faraday’s Law of electromagnetic induction (Eq.1).

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$  \hspace{1cm} (1)

Equation (1) is Faraday’s Law. This equation explains that the electric field develops as the time change of the magnetic field becomes shorter. That is, if the magnetic field rapidly develops over a short time, the electric field also develops.

The electric field responds to direct magnetic field fluctuations (section 3.3). In sections 3.1 and 3.2, a large current system generated in the sky was investigated, and both the magnetic field and the electric field were developed from the sudden current system. The details of the daytime geomagnetic pulsation have not been elucidated yet, but the geomagnetic field is characterized by direct vibration. Our findings presented in sections 3.1 and 3.2 suggest that it is not only the variation of the geomagnetic field, but also the equivalent current system in the sky that may contribute to the development of the electric field. However, this is not necessarily true for the geomagnetic pulsation. It is necessary to investigate each
disturbance phenomenon carefully, and also to investigate how much influence the terrain and other components may exert against the electric field with respect to geomagnetism and electric currents.

5. Conclusion
In order to predict the occurrence of GICs in Japan, it was hypothesized that it is necessary to consider the characteristics of GIEs. Therefore, the relationship between the observational values of Earth's geomagnetic and electric fields were examined.

At the time of a substorm, there is a time dependence with respect to the direction of origination of the electric field, and this can be considered to depend on the direction of the current system in the sky (e.g., FAC). There is space for continued discussion as to whether this electric field is reacts directly to currents in the sky, or both.

This study considers the correlation between Earth's magnetic and electric fields at the time of magnetic storm onset. Evaluation of the correlation between the raw data and the high-pass (30-minute) data, the correlation tended to be higher in the high-pass data. This indicates that the electric field responds to sudden magnetic field fluctuations more so than magnetic field fluctuations with their relatively long fluctuation cycles (e.g., daily fluctuations). This may be intuitively tied to Faraday's Law and may be the key to predicting electric fields in the future.

Regarding daytime geomagnetic pulsations, these were also observed in the electric field at the same time zone as the geomagnetic pulsation. Even in the absence of a large current system in the sky, the electric field fluctuates due to changes in the magnetic field. In the future, it will be necessary to analyse more detailed frequency data to further clarify the relationships presented here.

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