Statistical Study of the Long-Period Induced Geoelectric Field Caused by Magnetic Storms and Its Implication on Mantle Exploration

Siyuan Wu  
China University of Geosciences Beijing

Shuo Yao (✉ yaoshuo@cugb.edu.cn)  
China University of Geosciences Beijing  https://orcid.org/0000-0003-4267-0486

Jianjun Liu  
Polar Research Institute of China

Full paper

Keywords: Long-period (>105 s) Induced Geoelectric field, Magnetic Storms

Posted Date: September 22nd, 2020

DOI: https://doi.org/10.21203/rs.3.rs-78691/v1

License: ☕️ This work is licensed under a Creative Commons Attribution 4.0 International License.  
Read Full License
Statistical Study of the Long-Period Induced Geoelectric Field caused by Magnetic Storms and Its Implication on Mantle Exploration

Siyuan Wu, School of Geophysics and Information Technology, China University of Geosciences (Beijing), 100083, Beijing, China, wusiyuan826@gmail.com
Shuo Yao, School of Geophysics and Information Technology, China University of Geosciences (Beijing), 100083, Beijing, China, yaoshuo@cugb.edu.cn
Jianjun Liu, Polar Research Institute of China, 200136, Shanghai, China, liujianjun@pric.org.cn
Shuo Yao is the corresponding author.
Abstract

The ground induced geoelectric field caused by magnetic storms is not only a hazard, but also a helpful tool to explore the underground conductivity. Especially, the long period (>10^5 s, LP) induced field deserves more concerns as it could reach the mantle. However, the occurrence rate and the period range of the LP induced geoelectric field during different magnetic storms are unclear. This statistical work examines the occurrence and the period upper limit in the whole solar cycle 23. The geoelectric field and geomagnetic field measured continuously at Memambetsu observatory in Japan from 1989 to 2008 are studied. The LP electromagnetic field is identified by the wavelet coherence spectra. The results show that the LP induced geoelectric field stably occurred during magnetic storms in the solar cycle. The LP induced field in the first three months of each year is significantly different from that in the three months around super magnetic storms. The longest period of the induced geoelectric field during the magnetic storms is 9×10^5 s. The period upper limit of the induced δE_y is larger than that of the induced δE_x, which significantly increases with the storm intensity range. The distribution of the LP δE_x on the magnetic local time is asymmetric. To quantify the potential application of such a LP electromagnetic field on the mantle conductivity, we check the uncertainty of resistivity from inversion under the condition of plane-wave for layered medium. We set the sources to be the ring current and the field-aligned current in their real scales. As a result, the apparent resistivity is obtained within 10% uncertainty by δE_y, and within 20% by δE_x.

Keywords

Long-period (>10^5 s) Induced Geoelectric field, Magnetic Storms

Introduction

The long-period (LP, > 10^5 s) induced geomagnetic field disturbances have been measured and studied for many years (e.g. Lahiri and Price 1939; Banks 1969; Iyemori 1990; Constable and Constable 2004). The LP induced geomagnetic field disturbances centred at the period of two days are related to the ring current during the magnetic storms (e.g. Roberts 1984; Schultz and Larsen 1987; Banks and Ainsworth 1992). The induced geomagnetic field at the ground is dependent on both the current systems in the
ionosphere and in the magnetosphere, and the electrical conductivity structure in the deep earth (e.g. Sun et al. 2015; Fujii and Schultz 2002). This LP geomagnetic field disturbance can be used by the geomagnetic depth sounding (GDS) to deduce the electrical conductivity of earth interior (e.g. Banks 1969; Roberts 1984; Schultz and Larsen 1987; Banks and Ainsworth 1992; Olsen 1998). And the electrical conductivity of the earth mantle is a key factor in controlling the geomagnetic field reversal (Glatzmaier et al. 1999).

Since the current source is not completely known, a simplified zonal dipole assumption for the long period variation brings rather large error bars to the derived impedance (e.g. Schultz and Larsen 1987; Egbert and Booker 1992). Compared to the GDS method, the magnetotelluric (MT) method based on the simultaneously measured geoelectric field and geomagnetic field could calculate the impedance directly (e.g. Cagniard 1953; Tikhonov 1950; Rikitake 1951).

The induced EM field at period up to $10^4$ s is widely used in crust exploration by MT (e.g. Egbert 2007; Fujii et al. 2015). According to Srivastava (1965), the assumption of uniform plane wave is valid for the EM field at period below $10^5$ s. It is still unclear that what is the period upper limit of the induced geoelectric field related to magnetic storms, and if such field could be used as uniform plane wave in layered-structure medium (e.g. Chave and Jones 2012; Simpson and Bahr 2005).

As far as we know, the LP induced geoelectric field and its source have been rarely studied, as it is hard to obtain the continuous long-term measurement (e.g. Fujii et al. 2015; Egbert et al. 1992). Recently, Wu et al. (2020) reported the impact from the FAC on the direction and magnitude of the LP geoelectric field by comparing two magnetic storms. To check if the LP geoelectric field could be applied to the MT, it is important to investigate if such a field regularly generated by the magnetic storms, what is the period upper limit, and how could the source affect the period.

This statistical work, for the first time, shows the direct evidence of the stable existence of the LP geoelectric field, and checks its period upper limit in the solar cycle 22 and 23. The results also reveal the positive relation between the period limit of $\delta E_y$ and the ring current enhancement, with the measurements from the same ground geomagnetic observatory. The power distribution of $\delta E_x$ along the magnetic local time (MLT) indicates the domination by the field-aligned current. Considering the scales of the RC and the FAC, the induced LP field caused by the magnetic storms is proved to satisfy the plane-wave assumption for the layered medium. Therefore, this induced LP electromagnetic field during the magnetic storms could be used to reveal mantle conductivity. The geomagnetic field and geoelectric
field measurements, the geomagnetic indices, and the way we study the induced LP electromagnetic field are described in the section Data and Methods. The period upper limit and its relation to the storm levels are shown in the section Results. The current source scale and the plane-wave test are provided in the section Current Source Assumption and The Plane-wave Test. The superposition of the two current sources, and the possible application on the mantle conductivity are stated in the section Discussion. Finally, the period upper limit, the relation between the period upper limit and the magnetic storm level, and the applicability of the induced LP EM during on the layered medium are concluded.

Data and Methods

Data

The geomagnetic field and geoelectric field measurements at Memambetsu observatory (MMB) in Japan from 1989 to 2008 are available at http://www.kakioka-jma.go.jp/obsdata/metadata/en/products/list/mag/mmb. This work studies the induced geoelectric field in two groups of time intervals. The Group 1 contains the first three months of each year from 1998 to 2008. The magnetic storms in Group 1 have minimum SYM-H > -150 nT. Group 2 is composed of the three months centered at one of the 17 super storms from 1989 to 2004, shown in Table 1. The studied 17 super storms have the minimum SYM-H between 282 nT and 720 nT, which is from Meng et al. (2019).

The geomagnetic indices SYM-H and AE are available from the World Data Center (WDC) for Geomagnetism in Kyoto at http://wdc.kugi.kyoto-u.ac.jp. They are used to reflect the enhancement of the ring current (RC) and the auroral electrojet connected to the field-aligned current (FAC).

Identification of the induced LP field on the ground

We use the criteria below to automatically identify the LP induced geoelectric field, and calculate its period upper limit, the averaged power, and the duration in each magnetic storm. (1) The occurrence of the LP induced geoelectric field. We first calculate the wavelet power spectra of the geomagnetic field and the geoelectric field. One example of the super storm study is shown in Figure 1. Since the LP is defined as the period is longer than $10^5$ s, we focus on the spectra at period range from 26 to 250 hours. Next, we calculate the coherence coefficients between the geomagnetic wavelet power spectra and those of the geoelectric field. The areas having coherence coefficients larger than 0.8 at 95% significance level and outside the COI (cone of influence of wavelet) region are identified. They indicate the occurrence of the LP induced geoelectric field, named as region-1. The statistical results in Figure 2(a) and Figure 2(b)
Table 1. The studied 17 super storms from 1989 to 2004.

| SN | Dst\(_{\min}\) Time | SYM-H\(_{\min}\) | AE\(_{\max}\) | Studied Three Months |
|----|----------------------|----------------|-------------|---------------------|
| 1  | 1989-03-14 0130      | -720           | 2528        | 1989-02-01 to 1989-05-01 |
| 2  | 1989-09-19 0430      | -292           | No data    | 1989-08-01 to 1989-10-31  |
| 3  | 1989-10-21 1630      | -337           | No data    | 1989-09-01 to 1989-11-31  |
| 4  | 1989-11-17 2230      | -325           | No data    | 1989-10-01 to 1989-12-31  |
| 5  | 1990-04-10 1830      | -311           | 1742        | 1990-03-01 to 1990-05-31  |
| 6  | 1991-03-25 0030      | -337           | 3773        | 1991-02-01 to 1991-05-01  |
| 7  | 1991-10-29 0730      | -284           | 1960        | 1991-09-01 to 1991-11-30  |
| 8  | 1991-11-09 0130      | -402           | 1476        | 1991-10-01 to 1991-12-31  |
| 9  | 1992-05-10 1430      | -363           | 1819        | 1992-04-01 to 1992-06-30  |
| 10 | 2000-04-07 0030      | -320           | 1313        | 2000-03-01 to 2000-05-31  |
| 11 | 2000-07-16 0030      | -347           | 2844        | 2000-06-01 to 2000-08-31  |
| 12 | 2001-03-31 0830      | -437           | 1772        | 2000-02-01 to 2000-05-01  |
| 13 | 2001-04-11 2330      | -280           | 2146        | 2001-03-01 to 2001-05-31  |
| 14 | 2001-11-06 0030      | -320           | 2053        | 2001-10-01 to 2001-12-31  |
| 15 | 2003-10-30 2230      | -490           | 3560        | 2003-10-01 to 2003-12-31  |
| 16 | 2004-11-08 0630      | -394           | 2408        | 2004-10-01 to 2004-12-31  |
| 17 | 2004-11-10 1030      | -282           | 1856        | 2004-10-01 to 2004-12-31  |

- is from the region-1.

1. The duration of the storm. We calculate the period-averaged power curves for each component of the induced geoelectric field. As a result, the maximum power and the full width of half maximum (FWHM) is obtained for each component along time. The temporal segment equals to the FWHM is used to represent the storm duration, which is defined as region-2.

2. The LP induced geoelectric field during magnetic storms. The intersections between region-1 and
region-2 are defined as region-3, when the LP induced geoelectric field occurs during the magnetic storms.

The minimum SYM-H and the maximum AE are also chosen from region 3, respectively. The maximum period in region-3 is taken as the period upper limit of the induced geoelectric field during each storm.

In Figure 3(a), the period upper limit and the averaged power are from region-3. To exclude the power of the solar diurnal variation (24 hours), the studied period range in Figure 3(a) starts from 35 hours rather than 26 hours.

In addition, the related algorithms of wavelet transform are provided at http://paos.colorado.edu/research/wavelets by Torrence and Compo (1998), and at http://noc.ac.uk/marine-data-products/cross-wavelet-wavelet-coherence-toolbox-matlab by Grinsted et al. (2004).

**Examination of plane-wave assumption**

To examine the uncertainty of the apparent resistivity in the layered medium, it is necessary to know the period range and the source scale of the LP induced electromagnetic field. The theory is suggested by Srivastava (1965) and Price (1962). The electromagnetic field is assumed to be plane-wave. Starting from the Maxwell’s equations, they obtained (in emu)

$$Z(0) = \frac{i\omega}{\theta} \coth[\theta_1 h_1 + \coth^{-1}\left(\frac{\theta_1}{\theta_2}\coth(\theta_2 h_2 + \coth^{-1}\left(\frac{\theta_2}{\theta_3}\coth(\theta_3 h_3 + \ldots \coth^{-1}\frac{\theta_{n-1}}{\theta_n})\right))\right)]$$  \hspace{1cm} (1)

$$Z(0) = \frac{i\omega P + iQ}{\theta_1 R + iS}$$  \hspace{1cm} (2)

Here the $P$, $R$, $Q$, and $S$ are the real and imaginary parts of the right side in eq.(1).

$$|Z(0)|^2 = \frac{\rho_1}{2T} \frac{1}{(1 + v^4/k_1^4)^{1/2}} \frac{P^2 + Q^2}{R^2 + S^2}$$ \hspace{1cm} (3)

$$\rho_a/\rho_1 = \frac{1}{(1 + v^4/k_1^4)^{1/2}} \frac{P^2 + Q^2}{R^2 + S^2}$$ \hspace{1cm} (4)

$$\rho_a/\rho_1 = |Z(0)|^2 \cdot 2T/\rho_1$$ \hspace{1cm} (5)

In these equations, $2\pi/v$ is the horizontal scale of the source, $\sigma_n$ is the conductivity of the $n_{th}$ layer, $h_n$ is the thickness of the $n_{th}$ layer, $Z$ is the impedance, and $\theta_n$ equals to $\sqrt{v^2 + 4\pi i\omega \sigma_n}$. The current source scale of ring current (RC) is from Le et al. (2004), and that of field-aligned current (FAC) is from Chu et al. (2014) and Clauer and McPherron (1974).
Results

Stable occurrence and period upper limit of LP geoelectric field

Firstly, we check the existence of the LP induced geoelectric field with the normalized distribution of the lasting time along the period. Two groups of the magnetic storms are studied. One is composed of all the storms happened in the first three months from 1998 to 2008, which are mostly in the solar cycle 23. These storms have minimum SYM-H from -150 nT to -40 nT. Another group includes all the storms happened in the three month centered at a super storm. 17 super storms are recorded from 1989 to 2004, which have minimum SYM-H < -200 nT, listed in Table 1. The normalized duration is the lasting time of LP induced geoelectric field normalized by three months’ time (90 days). The period range and the normalized lasting time of the LP induced field caused by the magnetic storms from 1998 to 2008 are shown in Figure 2(a). The colored area represents the normalized lasting time of the LP induced field.

In the first panel of Figure 2(a), the induced $\delta B_x$ and $\delta E_y$ always cover the period range from $10^5$ s to $2.4 \times 10^5$ s. The longest period is about $5 \times 10^5$ s appearing in the storms of year 2000 and 2001. The mean period of the LP induced field is shown as the dotted line in the panels, which varies between $1.1 \times 10^5$ s and $1.6 \times 10^5$ s. In the second panel of Figure 2(a), the induced $\delta B_y$ and $\delta E_x$ cover the period range from $10^5$ s to $1.4 \times 10^5$ s. The longest period is still $5 \times 10^5$ s appearing shortly in the storms of year 2004. The lasting time of the $\delta B_y$ and $\delta E_x$ with period longer than $2.4 \times 10^5$ s is shorter than that of $\delta B_x$ and $\delta E_y$.

Since the lasting time is rather short, it is shown as dotted area in the second panel of Figure 1(a). The mean period varies from $1.1 \times 10^5$ s to $1.6 \times 10^5$ s. It is obvious that the LP geoelectric field occurs during all the magnetic storms, though the period ranges of them are different. We would like to mention that the LP induced field data is measured at the same observatory. Therefore, the period variation should be only attributed to the source in magnetosphere and ionosphere.

In both pairs of the LP induced field, the mean periods seem to be independent on the solar cycle. The period distributions of the geoelectric and geomagnetic field caused by all the magnetic storms happened in the Group 2 are shown in Figure 2(b). It is obvious that the period upper limit of the induced field increases to $9 \times 10^5$ s in the storms happened in year 2000 and 2001. The induced field of $\delta B_x$-$\delta E_y$ approaches to $3.6 \times 10^5$ s (100 hours) in 15 of 17 storms, shown in the first panel of Figure 1(b). 8 of 17 super storms generate the induced field $\delta B_x$-$\delta E_y$ at period longer than $5 \times 10^5$ s (150 hours). And 9 of 17 generate the $\delta B_y$-$\delta E_x$ at period longer than $5 \times 10^5$ s (150 hours). Besides, the normalized lasting time of
the enhanced LP field is significantly longer than that generated by storms in the first three month from 1998 to 2008.

It could be identified that the period upper limit is not linearly related to the SYM-H min nor to the $AE_{\text{max}}$ (not shown here). However, in the general trend of all the events, the storms Group 2 generate much longer period induced field than that in the Group 1. It seems that the stronger storms, which are related to stronger enhancement of RC, tend to generate longer period of LP induced field. It should be noted that the relation is not linear or monotonic. Thus, we decide to investigate the relation not by each SYM-H value, but by the SYM-H range.

**Relation between period upper limit and storm level**

The relation between period upper limit of the induced field and the storm level of all the storms happened in the Group 2 is shown in Figure 3(a). The studied induced field is in the period range from $1.2 \times 10^5$ s (35 hours) to $5 \times 10^5$ s (140 hours). It should be mentioned that the induced field is identified by the high correlation between $\delta B$ and $\delta E$. As a result, LP induced field could be identified in several regions of one storm. The longest period and minimum SYM-H of each region are recorded, which are shown in Figure 3(a). For the induced $\delta B_x$ and $\delta E_y$, the period becomes more concentrated on longer values when the storm is stronger. It means that the averaged period of LP induced field is linearly related to the storm level. Therefore, the relation between period upper limit and SYM-H minimum is not one-to-one, but band-to-band. It could be seen that the period limit has a wide range for the storms having minimum SYM-H from -210 nT to -50 nT. Similarly, the power of the LP induced $\delta B_x$ and $\delta E_y$ increases with stronger storms. For the induced field of $\delta B_y$ and $\delta E_x$, the band-to-band linear relation between period upper limit and storm level becomes weaker. We could like to clarify that the storms happened in the Group 1 could not be used to study the relation as they cover too small range of the minimum SYM-H from -40 nT to -150 nT.

**The enhancement of LP induced field on local time**

We next investigate the local time distribution of the LP induced field, which is shown in Figure 3(b). The studied storms are measured from 1998 to 2008 with minimum SYM-H varying between -150 nT and -40 nT. The LP induced $\delta B_x$ and $\delta E_y$ occur at all the local time. And the distribution is rather homogeneous. In contrast, the distribution of the LP induced $\delta B_y$ and $\delta E_x$ on local time is rather asymmetric. It is obvious that the enhancement of $\delta B_y$ and $\delta E_x$ never occur around noon. To exclude the effect of geomagnetic diurnal variation ($8.64 \times 10^4$ s) we only analyze the induced field at period longer
than $1.26 \times 10^5$ s (35 hours).

Current source analysis and the plane-wave test

Model of current sources for LP field

The statistical results show that the LP geoelectric field stably occurred during the magnetic storms in solar cycle 23, but having different period upper limits. The longest period of the LP induced field during the magnetic storms is $9 \times 10^5$ s, which is about 10 days. And the period is from $10^5$ s to $5 \cdot 10^5$ for super storms. For the moderate storms, the induced geoelectric field is at period range from $10^5$ s to $3 \cdot 10^5$ s.

The period limits of $\delta E_y$ show positive relation to the SYM-H range, which is related to the RC enhancement. The power distribution of $\delta E_x$ on the MLT shows the domination from the FAC. It is known that the enhancement of the ring current lasts for some days and the enhancement of field-aligned current stays for some hours. Since the period is related to the lasting time, the longer lasting time of RC enhancement generates the longer-period geoelectric field. The result supports that the stronger magnetic storms tend to have longer lasting time (Hutchinson et al. 2011).

However, it is difficult to understand how the shortly enhanced FAC generates the induced field at period longer than $10^5$ s. We suppose that the superposition of the RC and FAC may explain the period and power of LP $\delta E_x$ controlled by the FAC. In Figure 4 we give an illustration on $\delta B_y$ showing the superposed long-period induced field caused by the RC and the FAC. We use synthetic temporal signals including one sinusoidal sequence lasting for ten days at period of $10^5$ s and two triangle signals lasting for $3 \times 10^4$ s to check the superposed effect. The two signals represent the $\delta B_y$ generated by the RC and the FAC.

The synthetic $\delta B_y$ caused by RC, FAC and their superposition is shown in time domain in the top panel of Figure 4(a). In addition, both eastward and westward geomagnetic disturbances are considered shown as positive triangle and negative triangle. The wavelet power spectra of $\delta B_y$ are shown in the following panels. The right hand sub-panels are normalized time averaged power, the lower sub-panels are normalized frequency averaged power. The last panel of Figure 4(a) is the fourier’s power spectra of $\delta B_y$. It is clear that the superposed geomagnetic variation $\delta B_y$ still has the maximum power at period of $10^5$ s. It means that the amplitude of $\delta B_y$ and $\delta E_x$ at long period could be controlled by the FAC, though the enhancement of FAC is much shorter than RC.
The apparent resistivity obtained from plane wave assumption in layered medium

Assuming the current sources of the LP induced geoelectric and geomagnetic field are simply the RC and FAC, we check how accurate such a field could reflect the mantle conductivity. According to Srivastava (1965), Cagniard (1953) and Price (1962), we calculate the apparent resistivity of the layered-structure medium when the electromagnetic field is plane-wave. We use a layered conductivity model derived from over 10 years’ geomagnetic measurements, which is obtained by the spacecrafts and the observatories, provided in the Table 2 of Püthe et al. (2015). The model contains 40 layers from the surface down to infinite with the conductivity ranging from $1.8 \times 10^{-3}$ S/m to 2.36 S/m.

The results are shown in Figure 5. Since the ideal uniform plane wave has the infinite spacial scale, the LP induced EM field always has smaller scale. It is clear that the apparent resistivity obtained by smaller scale plane-wave EM field would become smaller than that obtained by ideal uniform plane-wave field at the same period. For different spacial scales of the current source, the period of $10^5$ s is critical for the accuracy of the apparent resistivity. Therefore, we show the smaller plot inside the larger one of Figure 4(b). The RC is enhanced globally and has large enough spacial scale (Le et al. 2004). The inversed apparent resistivity by the LP induced geoelectric field and geomagnetic field is still in accordance with that by the uniform plane wave at period of from $10^5$ s to $10^6$ s. It is known that the spacial scale of FAC is smaller. As a result, the apparent resistivity is less than that obtained from ideal uniform plane wave by 10% and 20% at period from $10^5$s to $5 \times 10^5$ s. The skin depth $(D)$ of this long-period EM field is estimated to be about 1500 km, assuming the resistivity being 100 $\Omega \cdot m$.

\[ D = \sqrt{\frac{\rho}{\pi f \mu_0}}. \]  

In the equation, $f$ is the frequency, $\mu_0$ is permeability constant of free space ($4\pi \times 10^{-7}$) and $\rho$ is the resistivity in unit of SI (Simpson and Bahr 2005; Chave and Jones 2012).

Discussion

The statistical results show that the period upper limit of $\delta E_y$ is longer than that of $\delta E_x$. During the magnetic storms having the minimum SYM-H $> -150$ nT, the longest periods of $\delta E_x$ in the magnetic storms are between $2 \cdot 10^5$ s and $4 \cdot 10^5$ s. When the minimum SYM-H is between -50 nT and -720 nT, the longest periods increase to between $2.5 \cdot 10^5$ s and $9 \cdot 10^5$ s. However, the relation between the period limit of $\delta E_x$ and the SYM-H is much weaker. Since the SYM-H represents the enhancement of the RC, it
means the period upper limit of $\delta E_y$ is controlled by the RC. And the stronger enhancement of RC tends
to have longer lasting time (Hutchinson et al. 2011), which generates longer period induced geoelectric
field.

The distributions of $\delta E_y$ and $\delta E_x$ on magnetic local time (MLT) are also different. The LP $\delta E_y$ shows
homogeneous distribution on MLT. It supports the domination of the RC, as the RC enhancement is
global and simultaneous. The distribution of LP $\delta E_x$ on MLT is significantly inhomogeneous. It is clear
that the power never appears around noon. This feature reflects the effect from the FAC (Clauer and
McPherron 1974; Chu et al. 2014; Wu et al. 2020). Through the superposition with the RC, the FAC
affects the LP geoelectric field. It should be noted that the measurements are from the same observatory.

So, the impact from the underground conductivity on the period and power of the geoelectric field could
be excluded. Such stably existed LP geoelectric field during the magnetic storms may reveal mantle
conductivity more accurately than the LP geomagnetic field only. The source currents of the $\delta E_y$ and
$\delta E_x$ are assumed to be the RC and FAC, respectively. And the source scales could be estimated with the
recent studies on the magnetosphere (Le et al. 2004; Chu et al. 2014) rather than the synthetic ones.

According to the source scales and the related period ranges, we check the plane-wave assumption for
the induced LP geoelectric and geomagnetic field during the magnetic storms. The result shows that the
LP $\delta E_y - \delta B_x$ satisfies the plane-wave assumption in the period range from $10^5$ to $10^6$ s. However, the LP
$\delta E_x - \delta B_y$ would generate an uncertainty from 10% to 20% on the apparent resistivity by inversion.

Conclusions

This statistical work studies the LP induced geoelectric field caused by the magnetic storms at the same
ground observatory in the solar cycle 23. If such a field is stably generated during magnetic storms, it
could be an important tool to explore the mantle conductivity. It is known that the measured geoelectric
field is controlled by both the current sources and the underground conductivity. Thus, it is necessary to
investigate the source and the related period range before the application on mantle conductivity.

To answer the above key questions, we analyze more than ten years’ measurements of the geoelectric
field and geomagnetic field, covering both the solar minimum and the solar maximum including 17 super
storms. Our work provides the direct evidence for the stable occurrence of LP induced geoelectric field
during magnetic storms. The period upper limit of such a field is from $2 \times 10^5$ s to $9 \times 10^5$ s. Besides,
the period ranges is related to the levels of the magnetic storms. Thus, the relation between the period
upper limit of $\delta E_y$ and the RC enhancement is revealed. In addition, the shorter period upper limit, the inhomogeneous power distribution on MLT, and the weak relation to the SYM-H index imply that the $\delta E_x$ is dominated by the FAC (Wu et al. 2020).

We check the superposition of RC and FAC on the power spectra in the frequency domain. It supports that the LP geoelectric field is generated by the two currents having different signatures in frequency domain. According to the recent studies on magnetosphere, we calculate the real scales of the RC and the FAC. With the period range and the source scale, the plane wave assumption for the LP field is used to obtain the apparent resistivity by inversion. The two pairs $\delta B_x-\delta E_y$ and $\delta B_y-\delta E_x$ have different results. The former generates the uncertainty less than 10%, while the latter generates the uncertainty from 10% to 20% on the apparent resistivity.

The results indicate that not only the harmful geomagnetically induced current, but also the helpful long-period induced geoelectric field caused by the magnetic storms deserve concerns. It is important to measure the long-period induced geoelectric field during the magnetic storms, which could be used to reveal the mantle conductivity. However, there is seldom continuous measurements of the geoelectric field longer than a week. With this LP induced field caused by the magnetic storms, the working period of the Magnetotellurics (MT) would increase up to one order. The 2D conductivity of the earth mantle around 1500 km depth may be obtained.

It is interesting to compare the MT inversion based on the C response with that by the measured induced geoelectric field and geomagnetic field in future. The mantle conductivity and the related thermal state are important constraints for the geomagnetic field reversal simulation (Glatzmaier et al. 1999). To improve the inversion accuracy at different places, more features of the source in magnetosphere and ionosphere and their effects on the different components of the LP induced geoelectric field should be investigated.

List of abbreviations

MT: Magnetotellurics

LP: Long-Period (>10^5 s)

GDS: Geomagnetic Depth Sounding

FAC: Field-Aligned Current

RC: Ring Current
MLT: Magnetic Local Time
EM: ElectroMagnetic Field
COI: Cone of Influence

Declarations

Availability of data and materials
The geomagnetic indices are from the World Data Center (WDC) for Geomagnetism in Kyoto at http://wdc.kugi.kyoto-u.ac.jp. The continuous measurements of the geoelectric field and geomagnetic field is from the Memambetsu observatory (MMB) in Japan at http://www.kakioka-jma.go.jp/obsdata/metadata/en/products/list/mag/mmb. The layered conductivity model is from Püthe et al. (2015).

Competing interests
The authors declare no competing interests.

Funding
The work on the induced geoelectric field during the magnetic storms is supported by the Chinese Meridian Project and by the fundamental research funds of central universities. The estimation for the field-aligned current is part of the project supported by the National Natural Science Foundation of China (NSFC) under contract 41431072 and 41674169. The study on the geomagnetic field variation is part of the Chinese "111" project under contract No. B20011.

Authors’ contributions
S. Yao conceived the idea and designed the research. S. Y. Wu processed all the ground measurements and carried out the statistical analysis. S. Yao and S. Y. Wu carried out the examination of plane-wave EM field assumption. J. J. Liu checked the scale of RC and FAC, and confirmed that the effect measured at Memambetsu could be from RC and FAC.

Authors’ information

Affiliations School of Geophysics and Information Technology, China University of Geosciences (Beijing), 100083, Beijing, China Siyuan Wu
School of Geophysics and Information Technology, China University of Geosciences (Beijing), 100083, Beijing, China Shuo Yao
Polar Research Institute of China, 200136, Shanghai, China Jianjun Liu
Acknowledgments

This work is supported by the Chinese Meridian Project, and by the fundamental research funds of central universities. The authors are supported by National Natural Science Foundation of China (NSFC) under contract No. 41204125, 41431072 and 41674169. S. Yao is also supported by State Key Laboratory of Biogeology and Environmental Geology, and by the Chinese "111" project under contract No. B20011. The authors acknowledge the use of geomagnetic indices from World Data Center (WDC) for Geomagnetism in Kyoto at http://wdc.kugi.kyoto-u.ac.jp, and the use of geoelectric field and geomagnetic field measurements at Memambetsu observatory (MMB) in Japan at http://www.kakioka-jma.go.jp/obsdata/metadata/en/products/list/mag/mmb. The authors thank Dr. L. T. Zhang and Dr. H. Dong for discussion.

Figures and Captions

Figure 1 The wavelet power spectra of the induced LP geomagnetic field and the geoelectric field Figure legends The Figure 1 shows the wavelet power spectra of the geomagnetic field and the geoelectric field from Feb. 1 to May. 1 in 1989. The super storm on March 14, 1989 is included in the studied three months. The first panel shows the power spectrum of $\delta B_y$. The white area is the cone of influence (COI) of the wavelet transform. The black line marks the coherence coefficient being 0.8. The horizontal dotted lines mark the period range from $10^5$ s to $5 \cdot 10^5$ s. The averaged power are shown in the second panel. The geomagnetic indices SYM-H and AE are shown in the third panel. The wavelet power spectrum and the averaged power of $\delta E_x$ are shown in the last two panels, respectively.

Figure 2 Period upper limits of the induced LP EM field during the magnetic storms Figure legends The sub-figure (a) shows the period upper limits of the induced LP EM field caused by the magnetic storms in the first three months from 1998 to 2008. The period ranges of the $\delta B_x-\delta E_y$ and $\delta B_y-\delta E_x$ are shown in the two panels, respectively. The colored area represents the duration of the induced field at each period, normalized by the three months’ time. The horizontal axis is the year from 1998 to 2008. The sub-figure (b) shows the period upper limits of the induced LP field caused by the magnetic storms in the three months including a super storm (minimum SYM-H < -200 nT). Each bar
shows the period ranges and the normalized duration of the induced LP field. The 17 storms are listed
in the order of time from 1989 to 2004 on the horizontal axis. The white circle marks the median period.

**Figure 3 The relation between the period upper limit and the SYM-H index**

*legends* The sub-figure (a) shows the relations between the period length, the mean power of $\delta B_x$, $\delta E_y$, $\delta B_y$, and $\delta E_x$, and the minimum SYM-H. The $x$-axis is the period length in logarithm 2. The $y$-axis is the averaged power in logarithm 2. Four levels of the storm intensity classified by the SYM-H minimum are shown in the different colors. The storms having SYM-H minimum in the four ranges between -687 nT and -528 nT, -528 nT and -369 nT, -369 nT and -210 nT, -210 nT and -51 nT are shown in black, blue, yellow, and pink, respectively. All the storms happen in the three months including a super storm from 1989 to 2004. The square marks the mean value of each SYM-H range. The sub-figure (b) shows the distributions of the power and the period upper limit of $\delta B_x$, $\delta B_y$, $\delta E_y$, and $\delta E_x$ along the local time. All the storms happen in the three months from 1998 to 2008, which have the SYM-H minimum varying from -40 nT to -150 nT. The $x$-axis is the local time from midnight to the next midnight. The color represents the period upper limit from $10^5$ s to $5 \times 10^5$ s varying from blue to red.

**Figure 4 The current source analysis** The figure shows the superposition of the LP field $\delta B_y$ generated by the RC and that by the FAC. The $\delta B_y$ caused by the RC is shown as a sinusoidal sequence in blue having the period of $10^5$ s and the unit amplitude in the sub-figure(a). The $\delta B_y$ caused by the FAC is shown as two opposite triangle signals in red lasting for $3 \times 10^4$ s having the amplitude of 5 times unit in the sub-figure(a). The superposition of the above two sequences is shown as black curve in the sub-figure(a). The wavelet power spectrum of $\delta B_y$ caused by the RC and by the FAC are shown in the sub-figure(b) and in the sub-figure(c), respectively. The right panels of the sub-figure(b) and (c) show the time averaged power. The bottom sub-panels of the sub-figure(b) and (c) show the period averaged power. The fourier spectra of the $\delta B_y$ caused by the RC and that caused by the FAC are shown as blue and red curves in the sub-figure(d). The fourier spectrum of the superposed $\delta B_y$ is shown as black curve in the sub-figure(d).

**Figure 5 The apparent resistivity obtained by plane-wave assumption for layered medium**

This figure shows the inversed apparent resistivity by the LP electromagnetic field under the uniform plane-wave assumption. The larger sub-figure shows the apparent resistivity calculated by the EM field having different source scales. The smaller figure focuses on the critical scales of the RC and the FAC under the uniform plane-wave assumption.
The wavelet power spectra of the induced LP geomagnetic field and the geoelectric field Figure legends
The Figure 1 shows the wavelet power spectra of the geomagnetic field and the geoelectric field from Feb. 1 to May 1 in 1989. The super storm on March 14, 1989 is included in the studied three months. The first panel shows the power spectrum of $\delta B_y$. The white area is the cone of influence (COI) of the wavelet transform. The black line marks the coherence coefficient being 0.8. The horizontal dotted lines mark the period range from $10^5$ s to $5.10^5$ s. The averaged power are shown in the second panel. The geomagnetic indices SYM-H and AE are shown in the third panel. The wavelet power spectrum and the averaged power of $\delta E_x$ are shown in the last two panels, respectively.
Figure 2

Period upper limits of the induced LP EM field during the magnetic storms. Figure legends: The sub-figure (a) shows the period upper limits of the induced LP EM field caused by the magnetic storms in the first three months from 1998 to 2008. The period ranges of the $\delta B_x-\delta E_y$ and $\delta B_y-\delta E_x$ are shown in the two panels, respectively. The colored area represents the duration of the induced field at each period, normalized by the three months' time. The horizontal axis is the year from 1998 to 2008. The sub-figure (b) shows the period upper limits of the induced LP field caused by the magnetic storms in the three years from 1998 to 2008.
months including a super storm (minimum SYM-H < -200 nT). Each bar shows the period ranges and the normalized duration of the induced LP field. The 17 storms are listed in the order of time from 1989 to 2004 on the horizontal axis. The white circle marks the median period.

Figure 3

The relation between the period upper limit and the SYM-H index Figure legends The sub-figure (a) shows the relations between the period length, the mean power of $\delta B_x$, $\delta E_y$, $\delta B_y$, and $\delta E_x$, and the minimum SYM-H. The x-axis is the period length in logarithm 2. The y-axis is the averaged power in logarithm 2. Four levels of the storm intensity classified by the SYM-H minimum are shown in the different colors. The storms having SYM-H minimum in the four ranges between -687 nT and -528 nT, -528 nT and -369 nT, -369 nT and -210 nT, -210 nT and -51 nT are shown in black, blue, yellow, and pink, respectively. All the storms happen in the three months including a super storm from 1989 to 2004. The square marks the mean value of each SYM-H range. The sub-figure (b) shows the distributions of the power and the period upper limit of $\delta B_x$, $\delta B_y$, $\delta E_y$, and $\delta E_x$ along the local time. All the storms happen in the three months from 1998 to 2008, which have the SYM-H minimum varying from -40 nT to -150 nT. The x-axis is the local time from midnight to the next midnight. The color represents the period upper limit from 105 s to 5x105 s varying from blue to red.
Figure 4

The current source analysis. The figure shows the superposition of the LP field $\delta B_y$ generated by the RC and that by the FAC. The $\delta B_y$ caused by the RC is shown as a sinusoidal sequence in blue having the period of 105 s and the unit amplitude in the sub-figure (a). The $\delta B_y$ caused by the FAC is shown as two opposite triangle signals in red lasting for 3 x 10^4 s having the amplitude of 5 times unit in the sub-figure (a). The superposition of the above two sequences is shown as black curve in the sub-figure (a). The wavelet power spectrum of $\delta B_y$ caused by the RC and by the FAC are shown in the sub-figure (b) and in the sub-figure (c), respectively. The right panels of the sub-figure (b) and (c) show the time averaged power. The bottom sub-panels of the sub-figure (b) and (c) show the period averaged power. The fourier spectra
of the $\delta B_y$ caused by the RC and that caused by the FAC are shown as blue and red curves in the sub-figure(d). The fourier spectrum of the superposed $\delta B_y$ is shown as black curve in the sub-figure(d).

Figure 5

The apparent resistivity obtained by plane-wave assumption for layered medium. This figure shows the inversed apparent resistivity by the LP electromagnetic field under the uniform plane-wave assumption. The larger sub-figure shows the apparent resistivity calculated by the EM field having different source scales. The smaller figure focuses on the critical scales of the RC and the FAC under the uniform plane-wave assumption.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- GraphicAbstractMainResultsv0916.png
- GraphicAbstractMainResultsv0916.png