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

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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 electric 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 δE_y and the ring current enhancement, with the measurements from the same ground geomagnetic observatory. The power distribution of δE_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.

(2) 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.

(3) 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)

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

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

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

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

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

$$\rho_a/\rho_1 = |Z(0)|^2 \cdot 2T/\rho_1 \quad (5)$$

In these equations, $2\pi/v$ is the horizontal scale of the source, σ_n is the conductivity of the n_{th} layer, h_n is the thickness of the n_{th} layer, Z is the impedance, and θ_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 δB_x and δE_y always cover the period range from 10^5 s to 2.4×10^5 s. The longest period is about 5×10^5 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 1.1×10^5 s and 1.6×10^5 s. In the second panel of Figure 2(a), the induced δB_y and δE_x cover the period range from 10^5 s to 1.4×10^5 s. The longest period is still 5×10^5 s appearing shortly in the storms of year 2004. The lasting time of the δB_y and δE_x with period longer than 2.4×10^5 s is shorter than that of δB_x and δE_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 1.1×10^5 s to 1.6×10^5 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 9×10^5 s in the storms happened in year 2000 and 2001. The induced field of δB_x - δE_y approaches to 3.6×10^5 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 δB_x - δE_y at period longer than 5×10^5 s (150 hours). And 9 of 17 generate the δB_y - δE_x at period longer than 5×10^5 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 $\text{SYM-H}_{\min}$ nor to the $\text{AE}_{\max}$ (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 1.2×10^5 s (35 hours) to 5×10^5 s (140 hours). It should be mentioned that the induced field is identified by the high correlation between δB and δE . 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 δB_x and δE_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 δB_x and δE_y increases with stronger storms. For the induced field of δB_y and δE_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 δB_x and δE_y occur at all the local time. And the distribution is rather homogeneous. In contrast, the distribution of the LP induced δB_y and δE_x on local time is rather asymmetric. It is obvious that the enhancement of δB_y and δE_x never occur around noon. To exclude the effect of geomagnetic diurnal variation (8.64×10^4 s) we only analyze the induced field at period longer

than 1.26×10^5 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 9×10^5 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 δE_y show positive relation to the SYM-H range, which is related to the RC enhancement. The power distribution of δE_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 δE_x controlled by the FAC. In Figure 4 we give an illustration on δB_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 3×10^4 s to check the superposed effect. The two signals represent the δB_y generated by the RC and the FAC.

The synthetic δB_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 δB_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 δB_y . It is clear that the superposed geomagnetic variation δB_y still has the maximum power at period of 10^5 s. It means that the amplitude of δB_y and δE_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 1.8×10^{-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 5×10^5 s. The skin depth (D) of this long-period EM field is estimated to be about 1500 km, assuming the resistivity being $100 \Omega \bullet m$.

$$D = \sqrt{\frac{\rho}{\pi f \mu_0}}, \quad (6)$$

In the equation, f is the frequency, μ_0 is permeability constant of free space ($4\pi \times 10^{-7}$) and ρ 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 δE_y is longer than that of δE_x . During the magnetic storms having the minimum SYM-H > -150 nT, the longest periods of δE_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 δE_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 δE_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 δE_y and δE_x on magnetic local time (MLT) are also different. The LP δE_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 δE_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 δE_y and δE_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 δE_y - δB_x satisfies the plane-wave assumption in the period range from 10^5 to 10^6 s. However, the LP δE_x - δB_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 2×10^5 s to 9×10^5 s. Besides, the period ranges is related to the levels of the magnetic storms. Thus, the relation between the period

upper limit of δE_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 δE_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 δB_x - δE_y and δB_y - δE_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 Pütke et al. (2015).

Competing interests

The authors declare no competing interests.

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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.

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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 δB_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 δE_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 δB_x - δE_y and δB_y - δE_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 δB_x , δE_y , δB_y , and δE_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 δB_x , δB_y , δE_y , and δE_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 5×10^5 s varying from blue to red.

Figure 4 The current source analysis The figure shows the superposition of the LP field δB_y generated by the RC and that by the FAC. The δB_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 δB_y caused by the FAC is shown as two opposite triangle signals in red lasting for 3×10^4 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 δB_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 δB_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 δB_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.

Figures

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 δB_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 105 s to 5.105 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 δE_x are shown in the last two panels, respectively.

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