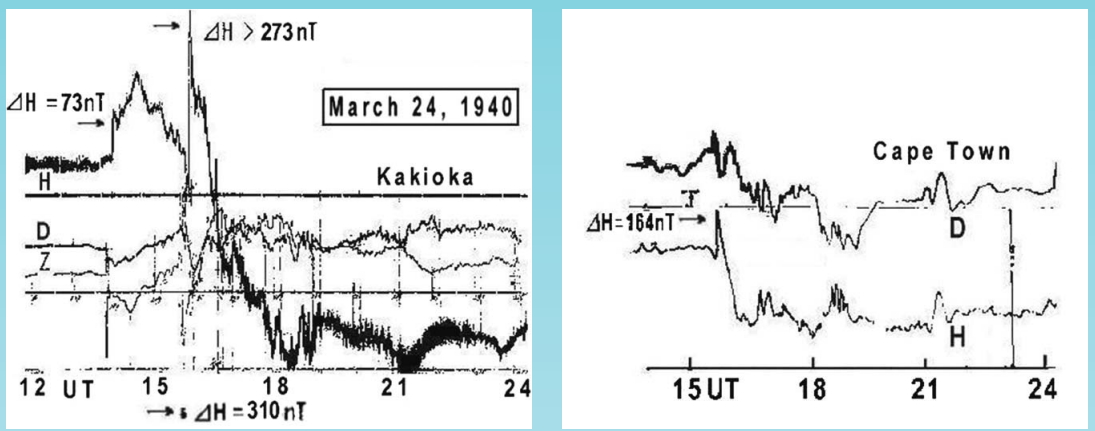
Earth, Planets and Space

Extremely Severe Space Weather and Geomagnetically Induced Currents in Regions with Locally Heterogeneous Ground Resistivity



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Earth, Planets and Space

Fujita *et al. Earth, Planets and Space* (2016) 68:51
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PREFACE

Open Access

Extremely severe space weather and geomagnetically induced currents in regions with locally heterogeneous ground resistivity

Shigeru Fujita[1*], Ryuho Kataoka[2], Ikuko Fujii[1], Antti Pulkkinen[3] and Shinichi Watari[4]

Large geomagnetically induced currents (GICs) triggered by extreme space weather events are now regarded as one of the serious natural threats to the modern electrified society. The risk is described in detail in High-Impact, Low-Frequency Event Risk, A Jointly-Commissioned Summary Report of the North American Electric Reliability Corporation and the US Department of Energy's November 2009 Workshop, June 2010. For example, the March 13–14, 1989 storm caused a large-scale blackout affecting about 6 million people in Quebec, Canada, and resulting in substantial economic losses in Canada and the USA (Bolduc 2002). Therefore, European and North American nations have invested in GIC research such as the "Solar Shield project" in the USA (Pulkkinen et al. 2009, 2015a). In 2015, the Japanese government (Ministry of Economy, Trade and Industry, METI) acknowledged the importance of GIC research in Japan. After reviewing the serious damages caused by the 2011 Tohoku-Oki earthquake, METI recognized the potential risk to the electric power grid posed by extreme space weather. During extreme events, GICs can be concerning even in mid- and low-latitude countries and have become a global issue.

From the scientific and technological aspect, GIC studies are interdisciplinary and include research in Earth's electromagnetism, magnetospheric and ionospheric physics, interplanetary physics, and solar physics. The GIC is determined by the geomagnetically induced electric field (GIE) and the DC characteristics of the electric power grid. GIEs are controlled by magnetic variations in the ground and the Earth's resistivity. Ground magnetic variations are composed of magnetic variations caused by magnetospheric and ionospheric disturbances and by currents induced in the ground. The magnetospheric disturbances in turn are driven by coronal mass ejections and other solar disturbances transmitted through interplanetary space. Furthermore, the effective application of a GIC study (e.g., disaster mitigation) requires assessment of how large and how often severe GICs occur in a specific area. Thus, the frequency of severe space weather events also needs to be characterized. At the same time, the heterogeneous distribution of the ground resistivity is important to assess local enhancements of the GIE. Scientists try to understand extreme space weather and predict a realistic GIC, and this special issue of 19 papers publishes recent research achievements about extremely severe space weather and the GIC in the realistic heterogeneous ground resistivity structure.

The influence of the heterogeneous resistivity structure is important for the reproduction of realistic GIEs and GICs from magnetic storm data. Ten papers in this collection address this topic. The influence of the heterogeneous resistivity structure to GIEs is investigated using the geoelectric data obtained continuously at Japanese magnetic observatories (Fujii et al. 2015). Love and Swidinsky (2015) also discuss the geoelectric data from the Kakioka Magnetic Observatory based on a two-layer lithosphere model. Goto (2015) calculates the GIE in the coastal zone with a strong spatial gradient in the resistivity and in the seafloor region with a homogeneous resistivity structure. Alekseev et al. (2015) construct the heterogeneous resistivity structure in the Earth, which is important for the evaluation of the GIEs. Pulkkinen et al. (2015b) demonstrate that the GIEs also can be locally enhanced when the source structure is highly heterogeneous. Next, realistic reproduction of GIEs and

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GICs from the magnetic storm data is reported by several papers. Püthe et al. (2014) calculate the GIE on the ground with heterogeneous resistivity structure driven by a real magnetic storm and accurately predict the GIE using their model. Beggan (2015) performs numerical studies of the GIE driven by the auroral electrojet. Beggan also uses a thin sheet model and estimates the GIC using electric power grid data from the UK. Watari (2015) predicts the GIC by using the transfer function between the observed GICs and the magnetic variations in Hokkaido, Japan. This technique was developed by Pulkkinen et al. (2007). Torta et al. (2014) study the GIC in the electric power grid in Spain by using a plane-wave model with uniform ground resistivity. Last, Xu et al. (2015) evaluate the induction effects driven by the magnetospheric ring current.

In space science and solar physics, detailed dynamics of the severe space weather events are still poorly understood. In addition, because GICs have societal implications, it is important to know the frequency of occurrence of severe space weather events. Therefore, we need to investigate the properties of large solar eruptions that can trigger extreme space weather events and can also transport of high-energy solar particles to the Earth. Nine papers discuss these topics. First, four papers discuss the physical processes associated with extreme magnetospheric disturbances such as the Carrington storm of September 1859 (the largest magnetic storm on record) (Keika et al. 2015), the March 13–14, 1989 magnetic storm (Nagatsuma et al. 2015), and the sudden commencement (SC) in 1940 (the largest SC since 1868) (Araki 2014). Keika et al. (2015) discuss the rapid recovery of the Carrington storm that may have been caused by the flow-out of the ring current associated with fast magnetospheric plasma convection. Nagatsuma et al. (2015) describe magnetospheric processes such as a long duration of the geosynchronous magnetopause crossing during the March 1989 storm, which lacks interplanetary data. They estimate interplanetary magnetic field (IMF) Bz of about −50 nT and solar wind speed of about 960 km/s. Similar to the large SC study by Araki (2014), Kubota et al. (2015) study characteristics of large SCs modeled with a global magnetosphere–ionosphere coupled MHD simulation. Next, three papers deal with statistical studies of the magnetospheric disturbances. Nakamura et al. (2015) study the auroral electrojets, and Minamoto et al. (2015) address the magnetic storms and SCs observed by the Kakioka Magnetic Observatory. The frequencies of occurrence of severe space weather are useful not only to the scientists but also to society. Hayakawa et al. (2015) present the historical records of auroras observed during the Chinese dynasty (Song) in tenth–thirteenth centuries. The last two papers report the characteristics of extreme solar flares and associated interplanetary transport of the energetic solar particles. Maehara et al. (2012, 2015) discuss the possibility of a super solar flare (Maehara et al. 2012) based on the solar type of stars observed by the Kepler space telescope. Kubo et al. (2015) present a model reproducing the transport of energetic solar particles that can pose a hazard to satellites.

Between 2011 and 2015, we held annual symposia about extreme space weather and a special symposium celebrating the centennial anniversary of geomagnetic observation at the Kakioka Magnetic Observatory in 2013. The intensive discussions at these symposia between participants from different fields stimulated deep insight into physical processes of these events, and a special issue was planned. In addition, a new Japanese research project about space weather (PSTEP—Project for Solar-Terrestrial Environment Prediction) will be conducted between 2015 and 2019 (http://www.pstep.jp/?lang=en). This project will support research on solar physics, interplanetary physics, magnetospheric physics, and GICs as well as research on the sun–climate relationship. The topics covered in this special issue provided an important springboard for the PSTEP project.

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FRONTIER LETTER Open Access

Statistical properties of superflares on solar-type stars based on 1-min cadence data

Hiroyuki Maehara*, Takuya Shibayama, Yuta Notsu, Shota Notsu, Satoshi Honda, Daisaku Nogami and Kazunari Shibata

Earth, Planets and Space 2015, **67**:59 DOI: 10.1186/s40623-015-0217-z
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Abstract

We searched for superflares on solar-type stars using Kepler data with 1-min sampling in order to detect superflares with a short duration. We found 187 superflares on 23 solar-type stars whose bolometric energy ranges from the order of 10^{32} to 10^{36} erg. Some superflares show multiple peaks with the peak separation of the order of 100 to 1,000 s which is comparable to the periods of quasi-periodic pulsations in solar and stellar flares. Using these new data combined with the results from the data with 30-min sampling, we found that the occurrence frequency (dN/dE) of superflares as a function of flare energy (E) shows the power-law distribution ($dN/dE \propto E^{-\alpha}$) with $\alpha \sim -1.5$ for $10^{33} < E < 10^{36}$ erg which is consistent with the previous results. The average occurrence rate of superflares with the energy of 10^{33} erg which is equivalent to X100 solar flares is about once in 500 to 600 years. The upper limit of energy released by superflares is basically comparable to a fraction of the magnetic energy stored near starspots which is estimated from the photometry.

We also found that the duration of superflares (τ) increases with the flare energy (E) as $\tau \propto E^{0.39 \pm 0.03}$. This can be explained if we assume the time scale of flares is determined by the Alfvén time.

Keywords: Superflares; Solar flares; Stellar flares; Solar-type stars; Extreme space weather events

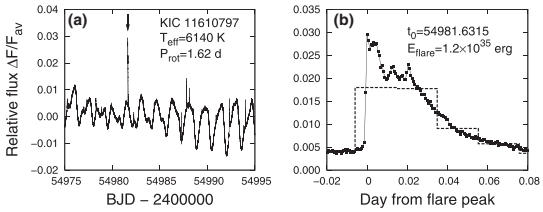

Figure 1

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FRONTIER LETTER Open Access

Regional-scale high-latitude extreme geoelectric fields pertaining to geomagnetically induced currents

Antti Pulkkinen*, Emanuel Bernabeu, Jan Eichner, Ari Viljanen and Chigomezyo Ngwira

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Abstract

Motivated by the needs of the high-voltage power transmission industry, we use data from the high-latitude IMAGE magnetometer array to study characteristics of extreme geoelectric fields at regional scales. We use 10-s resolution data for years 1993–2013, and the fields are characterized using average horizontal geoelectric field amplitudes taken over station groups that span about 500-km distance. We show that geoelectric field structures associated with localized extremes at single stations can be greatly different from structures associated with regionally uniform geoelectric fields, which are well represented by spatial averages over single stations. Visual extrapolation and rigorous extreme value analysis of spatially averaged fields indicate that the expected range for 1-in-100-year extreme events are 3–8 V/km and 3.4–7.1 V/km, respectively. The Quebec reference ground model is used in the calculations.

Keywords: Geomagnetically induced currents; Extreme events; Spatial scales

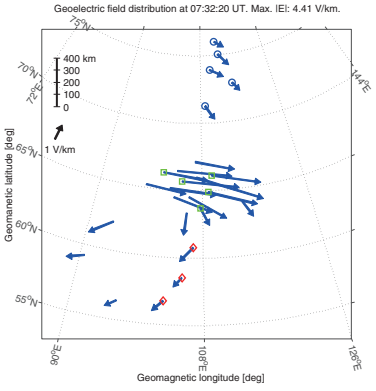

Figure 1

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FULL PAPER Open Access

Assessing the hazard from geomagnetically induced currents to the entire high-voltage power network in Spain

Joan Miquel Torta*, Santiago Marsal and Marta Quintana

Earth, Planets and Space 2014, **66**:87 DOI: 10.1186/1880-5981-66-87
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Abstract

After the good results obtained from an assessment of geomagnetically induced currents (GICs) in a relatively small subset of the Spanish power transmission network, we now present the first attempt to assess vulnerability across the entire Spanish system. At this stage, we have only included the power grid at the voltage level of 400 kV, which contains 173 substations along with their corresponding single or multiple transformers and almost 300 transmission lines; this type of analysis could be extended to include the 220-kV grid, and even the 110-kV lines, if more detailed information becomes available. The geoelectric field that drives the GICs can be derived with the assumption of plane wave geomagnetic variations and a homogeneous or layered conductivity structure. To assess the maximum expected GICs in each transformer as a consequence of extreme geomagnetic storms, a post-event analysis of data from the Ebre Geomagnetic Observatory (EBR) during the 2003 Halloween storm was performed, although other episodes coincident with very abrupt storm onsets, which have proven to be more hazardous at these mid-latitudes, were analyzed as well. Preferred geomagnetic/geoelectric field directions in which the maximum GICs occur are automatically given from the grid model. In addition, EBR digital geomagnetic data were used to infer statistical occurrence probability values and derive the GIC risk at 100-year or 200-year return period scenarios. Comparisons with GIC measurements at one of the transformers allowed us to evaluate the model uncertainties.

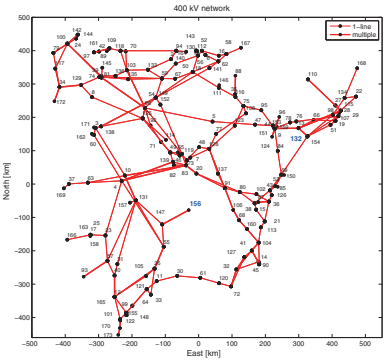

Figure 1

Keywords: Geomagnetically induced currents; GIC; Space weather; Natural hazards; Spain

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FULL PAPER Open Access

Reproducing electric field observations during magnetic storms by means of rigorous 3-D modelling and distortion matrix co-estimation

Christoph Püthe*, Chandrasekharan Manoj and Alexey Kuvshinov

Earth, Planets and Space 2014, **66**:162 DOI: 10.1186/s40623-014-0162-2
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Abstract

Electric fields induced in the conducting Earth by geomagnetic disturbances drive currents in power transmission grids, telecommunication lines or buried pipelines, which can cause service disruptions. A key step in the prediction of the hazard to technological systems during magnetic storms is the calculation of the geoelectric field. To address this issue for mid-latitude regions, we revisit a method that involves 3-D modelling of induction processes in a heterogeneous Earth and the construction of a magnetospheric source model described by low-degree spherical harmonics from observatory magnetic data. The actual electric field, however, is known to be perturbed by galvanic effects, arising from very local near-surface heterogeneities or topography, which cannot be included in the model. Galvanic effects are commonly accounted for with a real-valued time-independent distortion matrix, which linearly relates measured and modelled electric fields. Using data of six magnetic storms that occurred between 2000 and 2003, we estimate distortion matrices for observatory sites onshore and on the ocean bottom. Reliable estimates are obtained, and the modellings are found to explain up to 90% of the measurements. We further find that 3-D modelling is crucial for a correct separation of galvanic and inductive effects and a precise prediction of the shape of electric field time series during magnetic storms. Since the method relies on precomputed responses of a 3-D Earth to geomagnetic disturbances, which can be recycled for each storm, the required computational resources are negligible. Our approach is thus suitable for real-time prediction of geomagnetically induced currents by combining it with reliable forecasts of the source field.

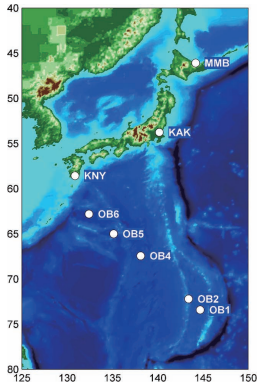

Figure 1

Keywords: Magnetic storms; Geomagnetically induced currents; Geoelectric field; Static shift; Distortion matrix; 3-D modelling

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FULL PAPER Open Access

Observed geomagnetic induction effect on *Dst*-related magnetic observations under different disturbance intensities of the magnetospheric ring current

Dan Xu*, Huaran Chen and Mengtan Gao

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Abstract

Based on the spherical harmonic expansion of geomagnetic disturbance observed on the mid-latitude surface of the Earth, external and internal field separation is conducted in which the external component is magnetic disturbance caused by the magnetospheric ring current and the internal component is that raised by the correspondingly induced currents within the Earth. The objectives are to evaluate the influences of the induced internal field on the surface magnetic observations and to reveal the response performance of internal geomagnetic induction under different strengths of magnetospheric ring current fluctuations for better understanding of the disturbance storm time (*Dst*) index variations. The results show that the ratio of the internal component to surface observation does not remain constant in storm time. During the main phase of the storm, the ratio variation follows the pattern of logarithmic growth with storm evolution up to the top value at the *Dst*-minimum; then, the ratio slowly decreases in the long recovery phase. Multiple small logarithmic growths are superimposed on the traces of internal ratios, corresponding to temporary ring current intensification during the storm main phase and amplifying the effect of this intensification on surface magnetic observations. With the intensification of magnetospheric storms from the level of (−200 *nT*, − 100 *nT*) to (−300 *nT*, − 200 *nT*) and (−500 *nT*, − 300 *nT*) classified with the *Dst*-minimum, the top value of the ratio averaged for each storm group in the superposed epoch analysis method increases from the value of 0.295 ± 0.014 to 0.300 ± 0.016 and 0.308 ± 0.015, respectively. It is demonstrated that the geomagnetic induction exceeds the linear relation with the intensification of the external field, which is physically reasonable and coincident with the Faraday's law of induction. Due to the effects of high induction of the oceans and lateral heterogeneity of electric conductivity distribution in the upper mantle of the Earth, the geomagnetic induction and its contribution to surface geomagnetic disturbance vary significantly among observatories. This factor should be considered in the research of magnetospheric current systems.

Keywords: Geomagnetic storms; Geomagnetic induction; *Dst* index

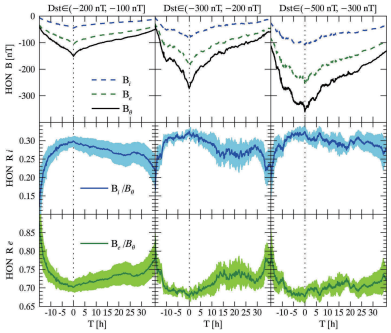

Figure 1

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Sensitivity of geomagnetically induced currents to varying auroral electrojet and conductivity models

Ciarán D Beggan

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Abstract

Geomagnetically induced currents (GIC) are created by the interaction of rapid changes in the magnitude of the magnetic field with the conductive subsurface of the Earth. The changing magnetic field induces electric currents, which are particularly strong along boundaries between regions of contrasting conductivity structure such as the land and sea. A technique known as the 'thin-sheet approximation' can be used to determine the electric field at the Earth's surface, which in turn allows the calculation of GIC in the earthing connections of high-voltage nodes within a power grid. The thin-sheet approximation uses a spatially varying conductance over the region of interest on a 2D surface, combined with a 1D layered model of upper lithosphere conductance. We produce synthetic models of the auroral electrojet in different locations over the United Kingdom (UK) and investigate the effects of varying the 2D thin-sheet model. We assess different two-dimensional surface conductance models and vary the underlying 1D conductivity models to simulate the effects of resistant through to conductive lithosphere. With an advanced network model of high-voltage electrical distribution grid, we compute the expected GIC at each node in the system given the input surface electric fields from the various synthetic electrojets and conductivity models. We find that the electrojet location is the primary control on the size of GIC, with conductivity being a second-order effect in general, though it can be locally important.

Keywords: Geomagnetically induced currents; Ground conductivity; Electric field

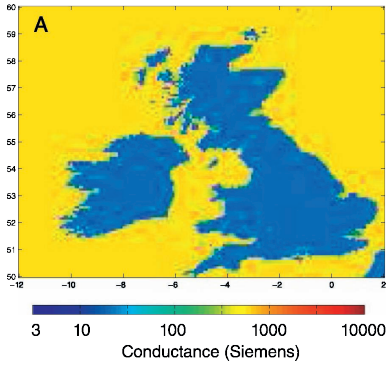

Figure 1

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FULL PAPER Open Access

Observatory geoelectric fields induced in a two-layer lithosphere during magnetic storms

Jeffrey J Love* and Andrei Swidinsky

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Abstract

We report on the development and validation of an algorithm for estimating geoelectric fields induced in the lithosphere beneath an observatory during a magnetic storm. To accommodate induction in three-dimensional lithospheric electrical conductivity, we analyze a simple nine-parameter model: two horizontal layers, each with uniform electrical conductivity properties given by independent distortion tensors. With Laplace transformation of the induction equations into the complex frequency domain, we obtain a transfer function describing induction of observatory geoelectric fields having frequency-dependent polarization. Upon inverse transformation back to the time domain, the convolution of the corresponding impulse-response function with a geomagnetic time series yields an estimated geoelectric time series. We obtain an optimized set of conductivity parameters using 1-s resolution geomagnetic and geoelectric field data collected at the Kakioka, Japan, observatory for five different intense magnetic storms, including the October 2003 Halloween storm; our estimated geoelectric field accounts for 93% of that measured during the Halloween storm. This work demonstrates the need for detailed modeling of the Earth's lithospheric conductivity structure and the utility of co-located geomagnetic and geoelectric monitoring.

Keywords: Magnetic storm; Induction hazard; Geomagnetic and geoelectric fields; Time-series analysis; Operational algorithm

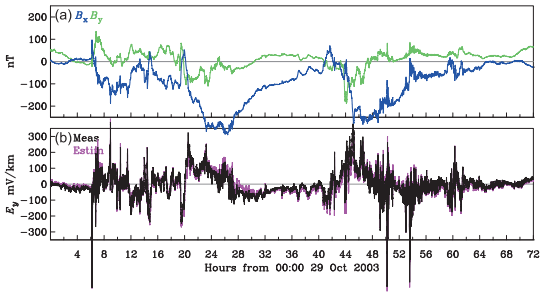

Figure 1

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FULL PAPER Open Access

The characteristics of geoelectric fields at Kakioka, Kanoya, and Memambetsu inferred from voltage measurements during 2000 to 2011

Ikuko Fujii*, Takashi Ookawa, Shingo Nagamachi and Takeshi Owada

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Abstract

Geoelectric voltages have been continuously observed at Kakioka, Kanoya, and Memambetsu for more than 50 years. The geoelectric fields obtained at the three sites for a recent 11-year period (2000 to 2011) were examined. The fields are mainly induced by variations in the geomagnetic field at periods of less than 10^5 s. The instability of the observation system causes a long-term trend in the longer period band. This long-term trend can be estimated and removed using the robust Kalman filter procedure which we modified to accommodate data containing outliers. The magnetotelluric (MT) impedance at the three sites was estimated using the original geoelectric field and the geomagnetic field at periods of 6 to 10^4 s, and the period was extended to 10^7 s at Kakioka and Memambetsu. Although the geomagnetically induced currents (GIC) at these sites may potentially be estimated using the MT impedance and geomagnetic data (if technological network information is available), the distortion effect should be corrected in order to obtain the correct regional geoelectric field. The eastward component of the geoelectric field at Kakioka shows a severe distortion effect, and the amplification factor was estimated to be approximately 10 from comparison with the C response at Kakioka. Conversely, the distortion effect on the eastward component of the geoelectric field at Memambetsu is almost none. The amplification factor for the northward component of the geoelectric field has not been estimated because of the lack of an independent response for comparison, although the MT response indicates a potentially large distortion at Memambetsu. Numerical modeling would be a useful tool to enable an improved estimation of this distortion.

Keywords: Geoelectric field; Kakioka; Memambetsu; Kanoya; Electromagnetic induction; Conductivity distribution; Geomagnetically induced current

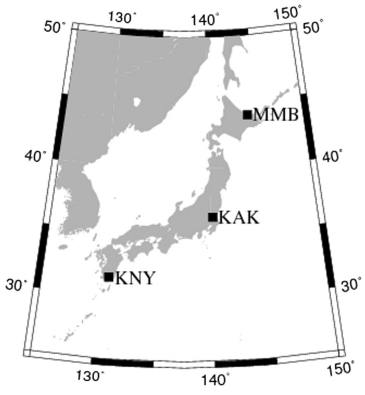

Figure 1

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FULL PAPER Open Access

What caused the rapid recovery of the Carrington storm?

Kunihiro Keika*, Yusuke Ebihara and Ryuho Kataoka

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Abstract

The geomagnetic storm during the Carrington event, which occurred on 2 September 1859, displayed extremely rapid recovery. The geomagnetic field increased by approximately 650 nT/h at Bombay, India, and by >300 nT/h in 1-h averaged data. Although the rapid recovery is considered due to a sudden increase in the magnetopause current, a sudden decrease of the ring current, or/and a sudden enhancement of the ionospheric currents, this study focuses on the ring current decay. The Carrington rapid recovery had a time constant (approximately 1 h) comparable to the storm development (i.e., decrease in the geomagnetic field), indicating that energy loss from the ring current region is predominantly controlled by E × B convection transport which is responsible for energy input during the storm main phase. This feature has led us to a hypothesis that the flow-out of dense ring current ions and injections of tenuous plasma sheet ions caused the rapid decay of the ring current and in turn the storm rapid recovery. This study examines whether the Carrington rapid recovery can be explained by the flow-out effect. We extend the empirical Burton's model to a model that takes into consideration a sudden change in solar wind density which is correlated with plasma sheet density. We first apply the extended Burton's model to previously observed four intense magnetic storms (Dst minimum < −200 nT) for which solar wind data are available. Using the best fit parameters found by forward modeling, the extended model estimates the recovery of the Carrington storm. The estimate indicates that a solar wind structure with a density bump by approximately 100 cm^{-3} (and southward interplanetary magnetic field (IMF) of 65 nT and solar wind speed of 1,500 km/s) can cause the rapid recovery under a continuous southward IMF condition. We conclude that the flow-out effect plays a significant role in producing the rapid recovery of the Carrington storm.

Keywords: Intense magnetic storms; Ring current; Storm rapid recovery; Flow-out loss; Carrington event; Plasma sheet density change

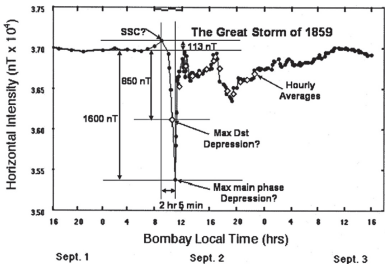

Figure 1

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FULL PAPER Open Access

Estimation of geomagnetically induced currents based on the measurement data of a transformer in a Japanese power network and geoelectric field observations

Shinichi Watari

Earth, Planets and Space 2015, **67**:77 DOI: 10.1186/s40623-015-0253-8
Received: 26 October 2014, Accepted: 19 May 2015, Published: 27 May 2015

Abstract

Geomagnetically induced currents (GICs) have the potential to cause electric power blackouts. Hence, it is important to study the effects of GICs produced by intense geomagnetic storms. The measurements of GICs were conducted at the Memanbetsu substation, Hokkaido, between December 2005 and March 2008. We obtain the complementary cumulative distribution function (CCDF) of the measured GICs and the empirical equation to estimate GICs using the GIC data and geoelectric field observation data. GICs associated with the past intense geomagnetic storms, e.g., the March 13–15 storm and the October 29–30, 2003 storm, are estimated.

Keywords: Geomagnetically induced current (GIC); Geomagnetic storm; Geoelectric fields; Space weather

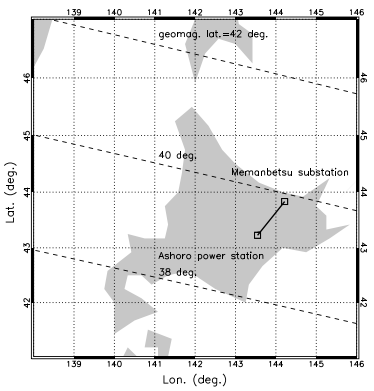

Figure 1

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FULL PAPER Open Access

Estimating the solar wind conditions during an extreme geomagnetic storm: a case study of the event that occurred on March 13–14, 1989

Tsutomu Nagatsuma*, Ryuho Kataoka and Manabu Kunitake

Earth, Planets and Space 2015, **67**:78 DOI: 10.1186/s40623-015-0249-4
Received: 31 October 2014, Accepted: 15 May 2015, Published: 27 May 2015

Abstract

The solar wind conditions of an extreme geomagnetic storm were examined using magnetic field observations obtained from geosynchronous satellites and the disturbance storm-time (Dst) index. During geosynchronous magnetopause crossings (GMCs), magnetic field variations at the magnetosheath, which is the modulated interplanetary magnetic field (IMF), were observed by geosynchronous satellite. The dawn to dusk solar wind electric field (VB_S) was estimated from the Dst index by using an empirical formula for Dst prediction; these data were then used to estimate the IMF and solar wind speed. This method was applied in the analysis of an extreme geomagnetic storm event that occurred on March 13–14, 1989, for which no direct solar wind information was available. A long duration of the GMC was observed after the second storm sudden commencement (SSC) of this event. The solar flare possibly associated with the second SSC of this storm event was identified as the March 12 M7.3/2B flare. The IMF B_z was estimated to be about −50 nT with a solar wind speed of about 960 km/s during the 5 h in which the main phase of the storm rapidly developed, assuming an Alfvén Mach number (M_A) during this period of more than 2.

Keywords: Extreme geomagnetic storm; Geosynchronous magnetopause crossing; Geomagnetic indices; Solar wind parameters

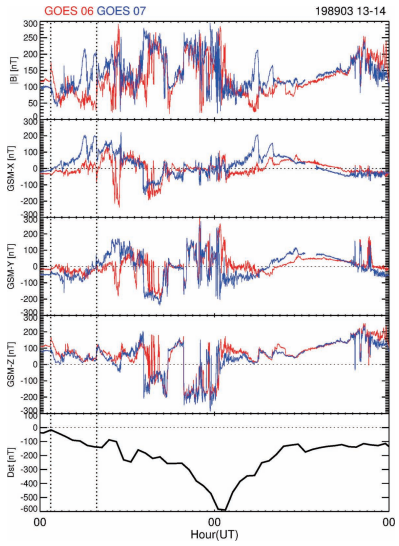

Figure 1

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FULL PAPER Open Access

Records of sunspot and aurora during CE 960–1279 in the Chinese chronicle of the Sòng dynasty

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Abstract

Records of sunspot and aurora observations in pre-telescopic historical documents can provide useful information about solar activity in the past. This is also true for extreme space weather events, as they may have been recorded as large sunspots observed by the naked eye or as low-latitude auroras. In this paper, we present the results of a comprehensive survey of records of sunspots and auroras in the *Sòngshǐ*, a Chinese formal chronicle spanning the tenth to the thirteenth century. This chronicle contains a record of continuous observations with well-formatted reports conducted as a policy of the government. A brief comparison of the frequency of observations of sunspots and auroras and the observations of radioisotopes as an indicator of the solar activity during corresponding periods is provided. This paper is the first step of our project in which we survey and compile the records of sunspots and auroras in historical documents from various locations and languages, ultimately providing it to the science community as online data.

Keywords: Aurora; Sunspot; Solar activity; Chinese chronicle; Historical resource

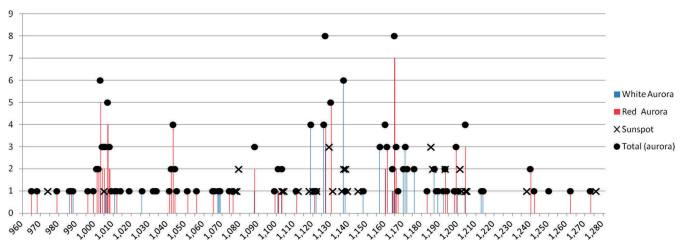

Figure 1

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FULL PAPER Open Access

Compilation of 3D global conductivity model of the Earth for space weather applications

Dmitry Alekseev*, Alexey Kuvshinov and Nikolay Palshin

Earth, Planets and Space 2015, **67**:108 DOI: 10.1186/s40623-015-0272-5
Received: 30 September 2014, Accepted: 13 June 2015, Published: 4 July 2015

Abstract

We have compiled a global three-dimensional (3D) conductivity model of the Earth with an ultimate goal to be used for realistic simulation of geomagnetically induced currents (GIC), posing a potential threat to man-made electric systems. Bearing in mind the intrinsic frequency range of the most intense disturbances (magnetospheric substorms) with typical periods ranging from a few minutes to a few hours, the compiled 3D model represents the structure in depth range of 0–100 km, including seawater, sediments, earth crust, and partly the lithosphere/asthenosphere. More explicitly, the model consists of a series of spherical layers, whose vertical and lateral boundaries are established based on available data. To compile a model, global maps of bathymetry, sediment thickness, and upper and lower crust thicknesses as well as lithosphere thickness are utilized. All maps are re-interpolated on a common grid of 0.25 × 0.25 degree lateral spacing. Once the geometry of different structures is specified, each element of the structure is assigned either a certain conductivity value or conductivity versus depth distribution, according to available laboratory data and conversion laws. A numerical formalism developed for compilation of the model, allows for its further refinement by incorporation of regional 3D conductivity distributions inferred from the real electromagnetic data. So far we included into our model four regional conductivity models, available from recent publications, namely, surface conductance model of Russia, and 3D conductivity models of Fennoscandia, Australia, and northwest of the United States.

Keywords: Global 3-D conductivity model; Geomagnetically induced currents; Magnetospheric substorms; Geoelectric field

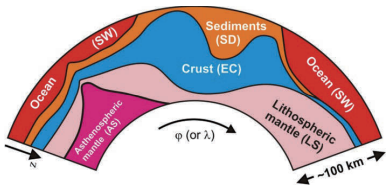

Figure 1

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LETTER Open Access

Historically largest geomagnetic sudden commencement (SC) since 1868

Tohru Araki

Earth, Planets and Space 2014, **66**:164 DOI: 10.1186/s40623-014-0164-0
Received: 26 September 2014, Accepted: 27 November 2014, Published: 9 December 2014

Abstract

Being stimulated by the previously reported large amplitude (202 nT at Kakioka) geomagnetic sudden commencement (SC) on 24 March 1991, we searched larger amplitude SCs in the past. We tried to collect old magnetograms and used the list of SC observed at Kakioka (27.5° gm. lat.) for the period 1924 to 2013 and Colaba (10.5°)-Alibag (10.3°) for 1868 to 1967. We found that the largest amplitude SC occurred on 24 March (the same day as 1991 SC), 1940. The H-component amplitude is larger than 273 nT at Kakioka and 310 nT at Alibag. We could also obtain the copy of the magnetogram of Cape Town (−33.3°) which shows 164 nT amplitude. The statistical analysis shows that the occurrence rate of SCs is less than 5% for amplitude larger than 50 nT and less than 1% for amplitude larger than 100 nT at both Kakioka and Alibag. Large amplitude SCs tend to occur during the declining phase of the solar activity. Finally, we discussed the possible increase of the dynamic pressure associated with the interplanetary shock causing the largest SC.

Keywords: Geomagnetic sudden commencement (SC); Solar activity; Largest SC; Interplanetary shock

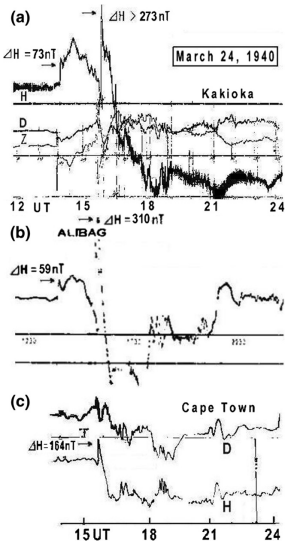

Figure 1

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LETTER Open Access

Global MHD simulation of magnetospheric response of preliminary impulse to large and sudden enhancement of the solar wind dynamic pressure

Yasubumi Kubota*, Ryuho Kataoka, Mitsue Den, Takashi Tanaka, Tsutomu Nagatsuma and Shigeru Fujita

Earth, Planets and Space 2015, **67**:94 DOI: 10.1186/s40623-015-0270-7
Received: 10 July 2014, Accepted: 10 June 2015, Published: 19 June 2015

Abstract

A sudden increase in the dynamic pressure of solar wind generates a prominent and transient change in ground-based magnetometer records worldwide, which is called a sudden commencement (SC). The magnetic field variation due to an SC at high latitudes shows a bipolar change, which consists of a preliminary impulse (PI) and main impulse (MI). The largest recorded SC had an amplitude of more than 200 nT with a spiky waveform at low latitudes, and the mechanism causing this super SC is unknown. Here, we investigate the cause of the super SC using a newly developed magnetosphere-ionosphere coupling simulation, which enables us to investigate the magnetospheric response to a large increase in the solar wind dynamic pressure. To simulate SCs, the dynamic pressure of the solar wind is increased to 2, 5, 10, and 16 larger than that under the stationary condition, and two different types of dynamic pressure increase are adopted by changing the solar wind density only or the solar wind speed only. It was found that the magnetic field variations of the PI and MI are several times larger and faster for a jump in the speed than for a jump in the density. It is inferred that a solar wind velocity of more than 2500 km/s in the downstream shock, which cannot be directly simulated in this study, would be consistent with the super SC.

Keywords: Sudden commencement; Extreme solar wind event; MHD simulation; Magnetosphere

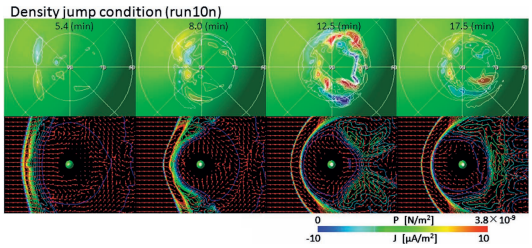

Figure 1

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LETTER Open Access

Statistical analysis of extreme auroral electrojet indices

Masao Nakamura*, Asato Yoneda, Mitsunobu Oda and Ken Tsubouchi

Earth, Planets and Space 2015, **67**:153 DOI: 10.1186/s40623-015-0321-0
Received: 29 December 2014, Accepted: 2 September 2015, Published: 16 September 2015

Abstract

Extreme auroral electrojet activities can damage electrical power grids due to large induced currents in the Earth, degrade radio communications and navigation systems due to the ionospheric disturbances and cause polar-orbiting satellite anomalies due to the enhanced auroral electron precipitation. Statistical estimation of extreme auroral electrojet activities is an important factor in space weather research. For this estimation, we utilize extreme value theory (EVT), which focuses on the statistical behavior in the tail of a distribution. As a measure of auroral electrojet activities, auroral electrojet indices AL, AU, and AE, are used, which describe the maximum current strength of the westward and eastward auroral electrojets and the sum of the two oppositely directed in the auroral latitude ionosphere, respectively. We provide statistical evidence for finite upper limits to AL and AU and estimate the annual expected number and probable intensity of their extreme events. We detect two different types of extreme AE events; therefore, application of the appropriate EVT analysis to AE is difficult.

Keywords: Auroral electrojet activity; AE AU AL index; Extreme value theory; Space weather

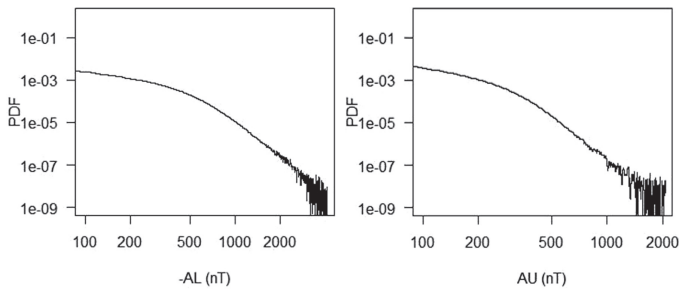

Figure 1

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LETTER Open Access

Frequency distributions of magnetic storms and SI+SSC-derived records at Kakioka, Memambetsu, and Kanoya

Yasuhiro Minamoto*, Shigeru Fujita and Masahiro Hara

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Received: 24 December 2014, Accepted: 24 November 2015, Published: 28 November 2015

Abstract

The Japan Meteorological Agency keeps records of geomagnetic phenomena observed at Kakioka (magnetic latitude, 27.47°), Memambetsu (magnetic latitude, 35.44°), and Kanoya (magnetic latitude, 22.00°). We used these records to examine the cumulative frequency distribution of magnetic storms, sudden impulses, and storm sudden commencements. The distributions of magnetic storms resemble the Gutenberg–Richter relation between earthquake frequency and magnitude used in seismology. The coefficients determined with the maximum likelihood method show that when the *H*-range of a magnetic storm at Kakioka is doubled, the frequency of the magnetic storm is about one seventh, for example. Intense magnetic storms occur less frequently than calculated by the functions. This statistical analysis proves that there are no significant differences between slopes of the frequency distribution functions of the magnetic phenomena at Kakioka, Memambetsu, and Kanoya.

Keywords: Magnetic storm; Sudden impulses; Storm sudden commencements; Power law

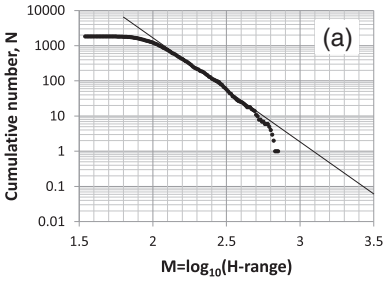

Figure 1

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LETTER Open Access

Numerical studies of geomagnetically induced electric field on seafloor and near coastal zones incorporated with heterogeneous conductivity distributions

Tada-nori Goto

Earth, Planets and Space 2015, **67**:193 DOI: 10.1186/s40623-015-0356-2
Received: 15 January 2015, Accepted: 10 November 2015, Published: 2 December 2015

Abstract

Abrupt changes of geomagnetic field can make large induced electric field and resultant electric current on the earth, which is called as geomagnetically induced current (GIC). It can yield damages to pipelines, cables, and other architectures. For understanding the phenomena and future risks of GIC, it is necessary to evaluate how the sub-surface electrical conductivity structure is important for the GIC because the heterogeneous conductivity structure in the crust and mantle affects the induced electrical current locally. The hazard prediction based on the homogeneous earth may result in the underestimation. Here, I introduce possible cases of geomagnetically induced electric field (GIE) on seafloor and near coastal areas, based on numerical forward simulations on one-, two-, and three-dimensional (1-D, 2-D, and 3-D) earth's structure including the sea layer. On the 1-D case, I show the possible amplitude of GIE on the seafloor, far from the coastal area. The second case study comes from 2-D forward simulation, in which the straightly elongated coastal line is assumed, and various sub-surface and sub-seafloor conductivity structures are imposed. The numerical results suggest that the amplitude of GIE on land becomes more than two times larger than that of the homogeneous earth without the sea layer. The width of land zone with larger GIE is about 20 km from the coast. In forward modeling with a simplified 3-D bathymetry, land electric field near the bay area increases with about ten times larger than that of the inland one. The seafloor GIE near the peninsula area also indicates about four times larger value than that of the other area at the same water depth. These phenomena can be explained by the boundary charge along the coastal area. I conclude that 3-D earth's conductivity structure including the realistic bathymetry and sub-surface and sub-seafloor structures should be essential and focused for the hazard assessment of GIC.

Keywords: GIC; Conductivity structure; Seafloor; Coastal effect

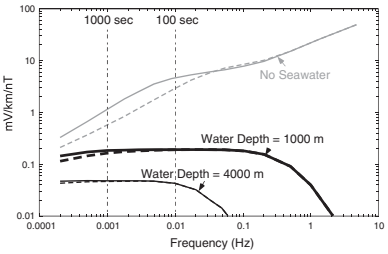

Figure 1

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TECHNICAL REPORT Open Access

Interplanetary particle transport simulation for warning system for aviation exposure to solar energetic particles

Yûki Kubo*, Ryuho Kataoka and Tatsuhiko Sato

Earth, Planets and Space 2015, **67**:117 DOI: 10.1186/s40623-015-0260-9
Received: 18 September 2014, Accepted: 2 June 2015, Published: 29 July 2015

Abstract

Background: Solar energetic particles (SEPs) are one of the extreme space weather phenomena. A huge SEP event increases the radiation dose received by aircrews, who should be warned of such events as early as possible. We developed a warning system for aviation exposure to SEPs. This article describes one component of the system, which calculates the temporal evolution of the SEP intensity and the spectrum immediately outside the terrestrial magnetosphere.

Findings: To achieve this, we performed numerical simulations of SEP transport in interplanetary space, in which interplanetary SEP transport is described by the focused transport equation. We developed a new simulation code to solve the equation using a set of stochastic differential equations. In the code, the focused transport equation is expressed in a magnetic field line coordinate system, which is a non-orthogonal curvilinear coordinate system. An inverse Gaussian distribution is employed as the injection profile of SEPs at an inner boundary located near the Sun. We applied the simulation to observed SEP events as a validation test.

Conclusions: The results show that our simulation can closely reproduce observational data for the temporal evolution of particle intensity. By employing the code, we developed the WArning System for AVIation Exposure to Solar energetic particles (WASAVIES).

Keywords: Solar energetic particles; Interplanetary particle transport; Radiation dose; Numerical simulation; Warning system

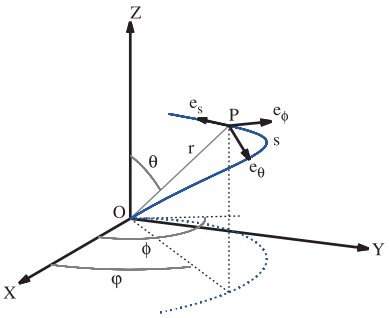

Figure 1

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5. The main text can have multiple free headings.
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7. References must follow the Springer Basic style.

Correspondence

If you have any questions, please contact editorial@earth-planets-space.com.

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Contents

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