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EQUINOCTIAL ASYMMETRY IN GEOMAGNETIC ACTIVITY IN AURORAL AND SUBAURORAL REGIONS

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ABSTRACT

Geomagnetically induced current (GIC) affect the normal operation of technological systems and are manifestations at ground level of space weather. The maximum GIC values are proxy to the maximum value of time derivatives of the horizontal field (dH/dt). 264 substorms events were obtained from IMAGE magnetometer data from Northern Europe, using Dst to determine the substorm events of varying strengths (from -90nT up to -1800nT) from 1992-2007, and were statistically analysed. In this study we found the maximum time derivatives of the horizontal magnetic field to be statistically significant in October at auroral and subauroral regions. Seasonal variations are also seen, Autumn being more geomagnetically active than other seasons. Our result shows a high correlation of 0.886 and 0.854 in auroral and subauroral regions between the max dH/dt and max AE index. The test of correlation between dH/dt and measured ionospheric response (AE) shows a close relationship between dH/dt and geomagnetic disturbance, and which could improve our space weather prediction systems.

Keywords: Time derivatives of geomagnetic fields, auroral and subauroral region, geomagnetic disturbances, geomagnetically induced current (GIC), seasons.

INTRODUCTION

Geomagnetic activity remains a major concern in space weather effect. When charges are streaming away from the Sun in the form of magnetised solar wind, the interaction of solar wind with Earth's magnetic field leads to plasma convection and electric currents which form within the Earth's magnetosphere. Energy loaded in the geomagnetic tail in form of plasma and magnetic fluxes are released intermittently. During the geomagnetic storm, most of the energy moves away from the Earth, but a significant part is accelerated towards us, leading to particle precipitation at high latitude, as a result of rapid fluctuations of electric current in the magnetosphere and ionosphere. This change is called geomagnetic activity. The geomagnetic activity is accompanied by an induced electric current field, which drives the current in ground based technological systems such as electric power transmission grids, oil and gas pipelines, telecommunication cables and railway equipment. All these are manifestations of the ground effect of space weather at high geomagnetic latitude, where they have been known to cause problems. It was confirmed that geomagnetic activities are usually associated with equatorial region current intensification which can be the source of large magnitude and long duration of the GIC in power grids at low and equatorial regions (Erinmez *et al.*, 2002). These long duration of GIC have caused extensive damage to exposed transformer at low latitude locations (Makhosi and Coetzee, 2004). Kappenman (2005, 2006) observed that October 28th -31st, 2003 storms, that Kelvin-Helmholtz shearing may be responsible for pulsation that can cause large GIC.

GIC are driven by the horizontal electric field induced at the Earth's surface due to time-varying or fast-moving strongly inhomogeneous ionospheric current systems and affected by the Earth's conductivity structure. The auroral substorms play an important role in the creation of large GIC. However, there exist a number of other phenomena that cause large GIC. Two important categories, besides substorms, are geomagnetic pulsations and sudden geomagnetic commencements created by the dynamic pressure pulses in the solar wind, which are global threat to technological conductor systems on the ground. (Pulkkinen *et al*., 2005; Leonard *et al*., 2000; Kappenman, 1996; Kataoka and Pulkkinen, 2008). The GIC calculation can be divided into geophysical and engineering steps. The geomagnetic steps is independent of the network considered and requires knowledge of ionospheric current or ground magnetic data and of the Earth conductivity, while engineering steps contain the actual calculation of the resulting GIC (Pirjolar, 2000, 2002). Several techniques have been adopted to calculate the geomagnetic field at the auroral region, where the proximity of the ionospheric current may produce difficulties. They are application of complex image method (CIM), plane wave method and network parameters with geomagnetic field (Boteler *et al*., 1998; Pirjola and Viljanen, 1998; Lehtinen and Pirjola, 1985;

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Pulkkinen *et al*., 2001).

Following the basic fundamentals of Faraday's law, linking temporal changes of the magnetic flux to the electromotive force, the geoelectric field is accompanied by a varying geomagnetic field, indicating that the time derivatives of the ground magnetic field dB/dt provide an excellent proxy for GIC activity, especially with the horizontal component (dH/dt) (Viljanen *et al*., 2001, 2006). Also, computing the geoelectric field from the measured ground geomagnetic field offers a statistical estimation of the likely occurrence of GIC in a particular system or region.

In this paper, we study the occurrence of geomagnetic activities in auroral and subauroral regions using measurements of the variations of the horizontal component of the geomagnetic field at the magnetic observatories of Soroya and Nurmijarvi, whose geomagnetic latitudes are close to the northern and southern borders of Finland.

DATA ANALYSIS

Our database consists of 264 substorms observed by the IMAGE magnetometer network in Northern Europe. We used one hour resolution of Dst (Disturbance storm time) index data from Kyoto index which was designed to describe the axially symmetric variation of the geomagnetic field during the storms (Sugiura, 1964). Also we looked at the activity level of Dst between -90nT and above to determine the substorms for each day between 1992 and 2007. The activity levels of the Dst binned in this study were used to examine the ground geomagnetic field around the dates of events between 1992 and 2007 in auroral and subauroral regions.

In this data-set, there are 142 substorms from the Soroya observatory (auroral region with geomagnetic latitude between 65^0N and 75^0E) available from 1992-2007. Also 122 substorms were obtained from Nurmijarvi observatory (subauroral region with geomagnetic latitude between 65^0N and 55^0E) from 1992-2007 (see Fig. 1). The time resolution of the magnetic data is 1minute.

To examine the features of the horizontal geomagnetic field, which is proxy to GIC at the Earth's surface from 1minute data, we computed the time derivatives of the ground horizontal magnetic field:

$$\frac{dH}{dt} = \sqrt{\left(\left(\frac{dY}{dt}\right)^2 + \left(\frac{dX}{dt}\right)^2\right)}$$

to give a reasonable measure of the induction or GIC activity (Viljanen *et al*., 2001), by subtracting successive values and dividing by the sampling interval.

Seasonal variation of maximum time derivatives and maximum horizontal magnetic field

The daily maximum values of dH/dt and H were computed from each substorm event at the Soroya observatory and Nurmijarvi IMAGE site. During these substorms, max dH/dt was larger in the auroral region than the sub auroral region. The monthly occurrence of dH/dt after the substorm onset at each available magnetometer site gives an overview of GIC activity during substorms. As seen in figure 2, the disturbance of max dH/dt peaks sharply in October, with another peak in April in the auroral region. Meanwhile in the subauroral region October and November show maximum occurrences, with subsequent ones in February and April.

The max H possesses the same features at auroral and subauroral regions, with maximal occurrences in October, November, February and April. Also from figure 2, we noticed that the scale of max dH/dt are different (500000nT/s in auroral region and 140000nT/s in subauroral region) and the scale of max H intensity are similar and greater for subauroral than auroral regions (300000nT/s in auroral region and 350000nT/s).

Considering the seasonal variation using max dH/dt and max H from 1992-2007 at Soroya and Nurmijarvi observatories, the seasonal periods used in this study are centred on Winter, Spring, Summer and Autumn and are divided by the days of the year. Winter is defined as 22nd December-22nd March, Spring is 22nd March-22nd June, Summer is 22nd June-22nd September, and Autumn is 22nd September-22nd December.

It is quite clear from figure 3 (a-b) that Autumn has the highest value of max dH/dt, with another peak in Spring in the auroral region. Also in the subauroral region, Autumn has the maximum values of occurrence with another peak in Spring. However, the differences between Spring, Winter and Summer are not well pronounced. In the subauroral region, the max H intensity is not well pronounced in Winter, Spring and Summer, but shows a high value in Autumn, while in the auroral region Autumn and Spring shows high values. As a result, more storms occur during Autumnal and Spring than Winter and Summer. Semiannual variation in geomagnetic field H consists of two equinoctial minima probably caused by the increase in westward ring current and substorm westward auroral electrojet in equinoctial months. Also more geomagnetic substorms occur in Autumn, the IMF-effect which increases the solar wind-magnetosphere interaction, might also cause more geomagnetic activity during Autumn and Spring, when the Earth is favourably connected to the solar wind from the active solar regions as equinoctial increase in solar wind speed. It is also suggested that the semiannual variation of geomagnetic activity, which is enhanced in the auroral region, affects every day amplitude of the diurnal and semidiurnal

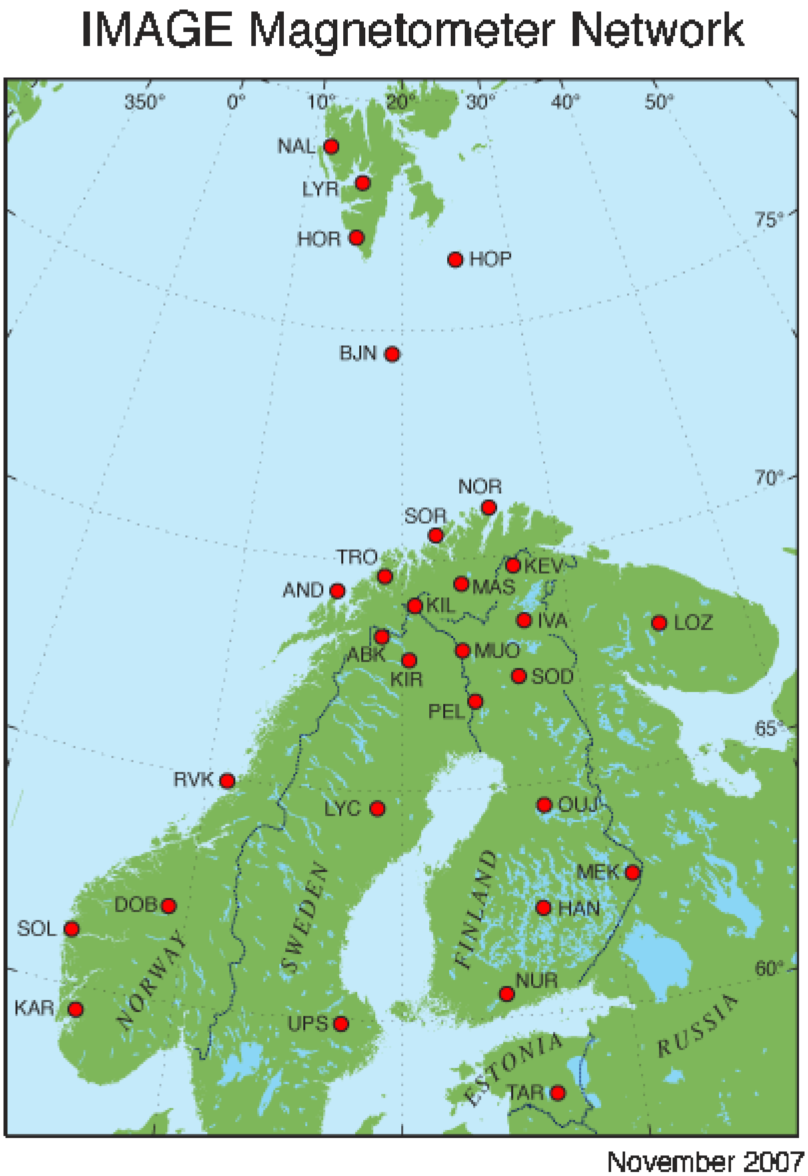
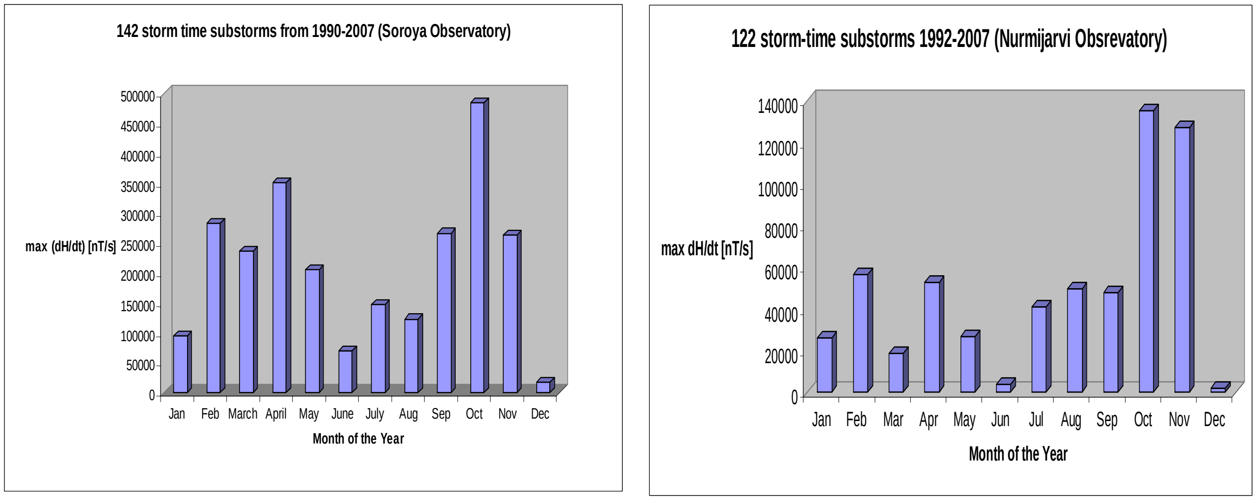


Fig. 1. SOR and NUR indicate Polar and Pre polar in the map of Finland.

variations within this region. Therefore auroral electrojets, which are the primary currents affected by substorms, enhance the variation around equinoxes, even when geomagnetic activity is low. Rosen (1966) and Campbell (2003) associated the observed enhancement in geomagnetic activity at the equinoxes with the favoured alignment of the magnetosphere boundary with respect to the solar wind interaction at these times.

Figure 4 (a and b) illustrates the distribution of substorms as a function of seasons, gives a strong support for the existence of geomagnetic activity which increases in the period of the Autumn (October- November) and Spring (March-April) that is Russell and McPherron effect (1973) implies that the sunspot number increases the base level of geomagnetic activity increases, this represents a level of geomagnetic activity which is directly related to the sunspot number. These changes are ultimately tied to variations associated with the sunspot cycle and are manifestation of space weather. Thompson (1993) also considered that the contribution to geomagnetic disturbance is linked with solar maximum. It is reasonable to expect that variation of geomagnetic activity during the maxima phase of a solar cycle can be directly related to the sunspot maximum.



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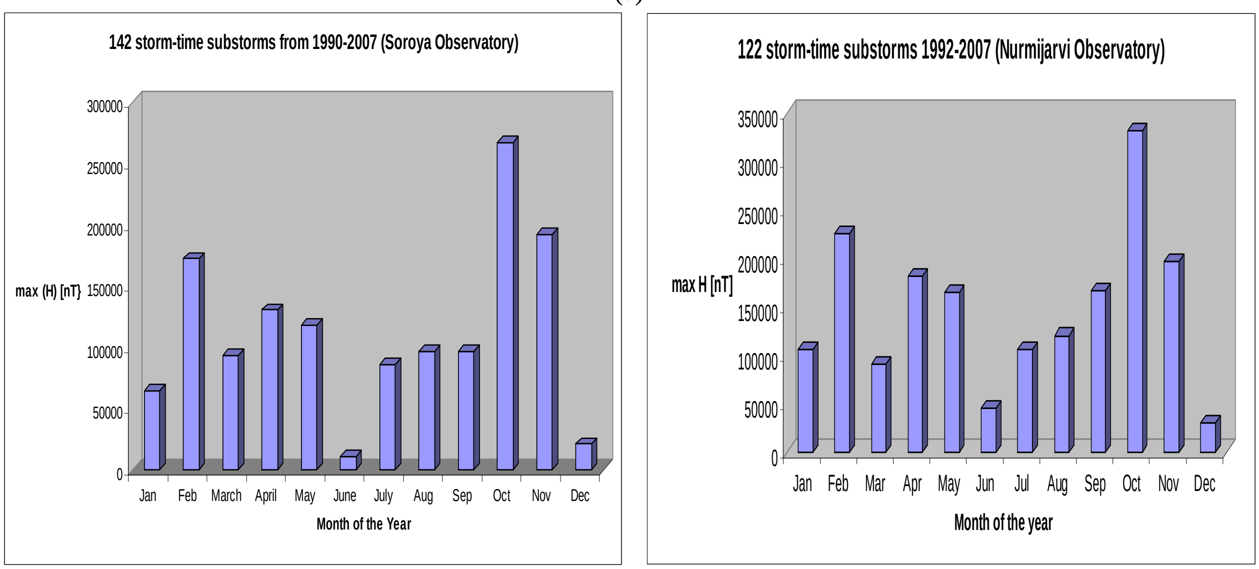


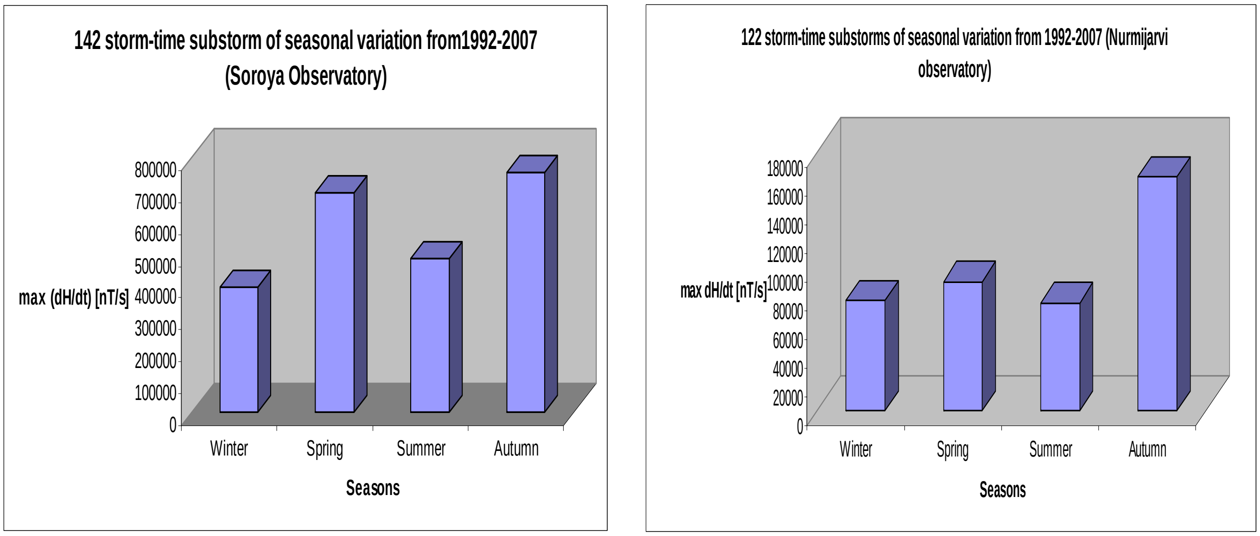
(b)

Fig. 2. Monthly variation of max dH/dt from 1992-2007 and 1992-2007 (upper panel) and monthly variation of max H from 1992-2007 and 1992-2007 (lower panel).

We also studied the diurnal distribution for the hours with max dH/dt as shown in figure 5. An interesting result was observed in the auroral region (Soroya), with maximum occurrence in the early morning and with another occurrence at midnight, while in the hours prior to midday the events disappeared. Similarly, events almost disappeared before the midday at subauroral region (Nurmijarvi). Figure 5 illustrates the GIC is related to the westward auroral electrojet which circulate on the night side. The westward auroral electrojet is stronger than the eastward one which circulates on the dayside. This implies that night time is more significant than the day time. Petrinic *et al*. (2000) using X-ray emissions, consistently showed that intense auroral emissions are more likely when a given region is in darkness than when the same region is in daylight, and supported the idea that sunlight reduces the probability of establishing a large field line potential drop. Newell *et al*. (1996) also related the frequent occurrence of electron acceleration in dark and sunlit conditions indicated by the solar zenith. It was observed that electron acceleration is common in darkness indicating that darkness is a factor for the field aligned potential drop to be produced.

Regression analysis of max dH/dt, max H and max AE

Magnetic field measurement on the ground monitors the strength of ionospheric current associated with auroral activity. The AE index provides a quantitative measure of energy dissipated in the ionosphere by the coupled Sun–Earth system. A regression analysis was performed to test the relationship between the time derivatives of the horizontal geomagnetic field as an activity indicator and



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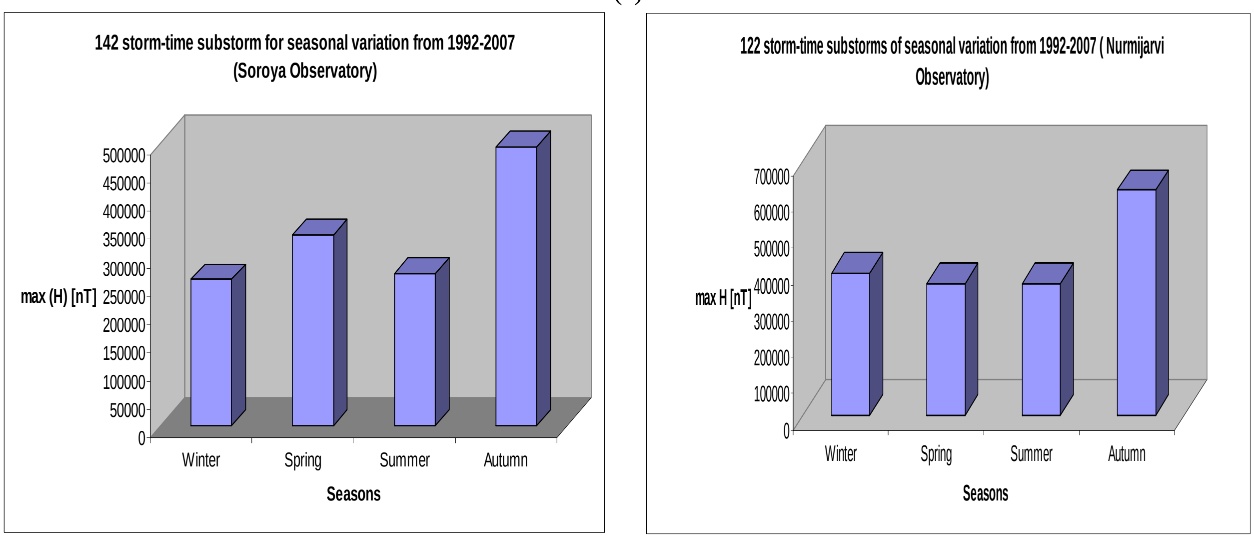


(b)

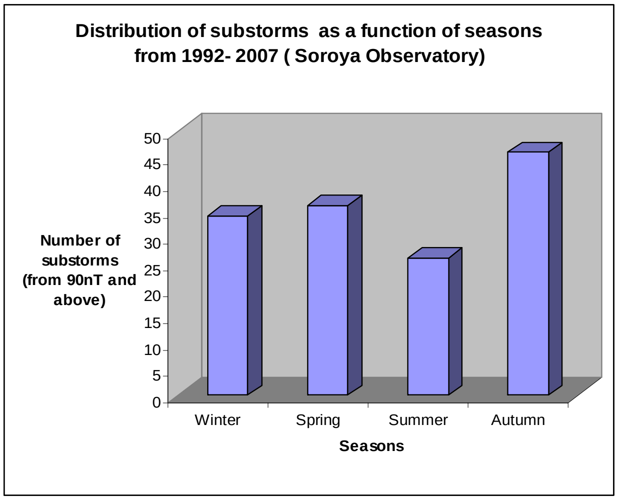
Fig. 3. (a) Seasonal variation of max dH/dt from 1992-2007 and 1992 -2007 and (b) Seasonal variation of max H from 1992- 2007 and 1992 -2007.

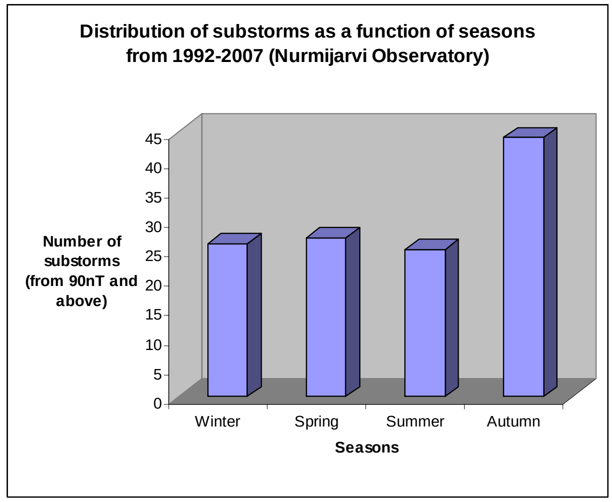
the AE index at the Soroya and Nurmijarvi observatories. The max dH/dt with max AE index was compared, may improve our prediction possibilities.

Figure 6 illustrates the regression analysis, at the Soroya (auroral region), there is a high correlation of 0.886 between max dH/dt and max AE with a coefficient of determination (r^2) of 0.7858. This implies that 78.58% of max dH/dt can be accounted for by using the AE index. A correlation coefficient of 0.955 was obtained between the maximum horizontal magnetic field intensity (H) and the AE index, with a coefficient of determination (r^2) of 0.9129 implying that 91.29% of max H can be accounted for by using the AE index.

In Nurmijarvi (subauroral region), a correlation coefficient of 0.854 exists between max dH/dt and max AE indices, with a coefficient of determination (r^2) of 0.7287. This implies that 72.87% of max dH/dt can be accounted for using the max AE index. We also estimated the geomagnetic activity using max H and max AE index, with high correlation coefficient of 0.8959 with coefficient of determination (r^2) 0.8027 which implies that 80.27% of max H can be accounted for using max AE index .

In addition, considering the correlation coefficient and coefficient of determination between the max dH/dt, max H, max AE and minimum value of Dst (from -90nT and above for each day between 1992-2007 which are used to select the substorms) at Nurmijarvi, with a correlation





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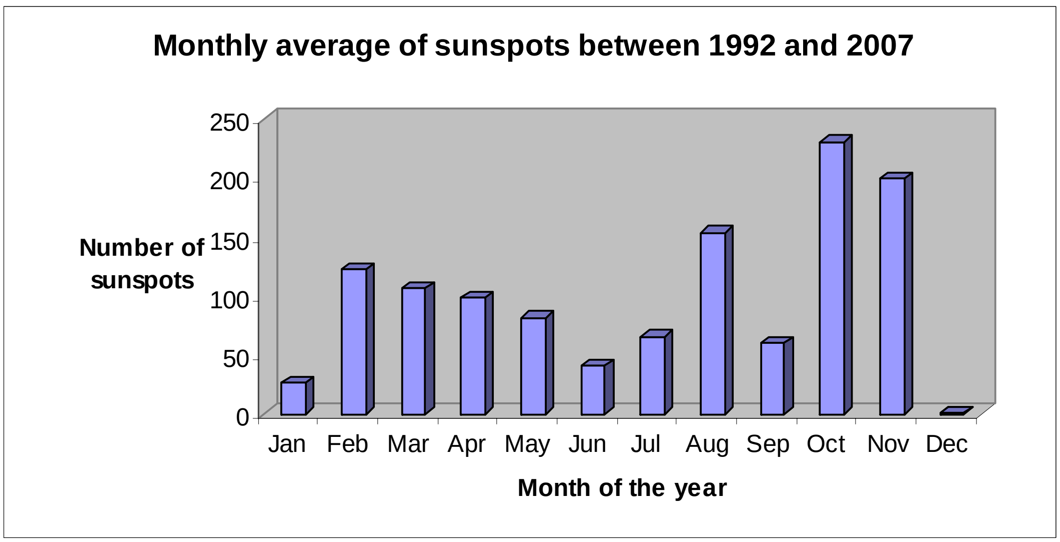


(b)

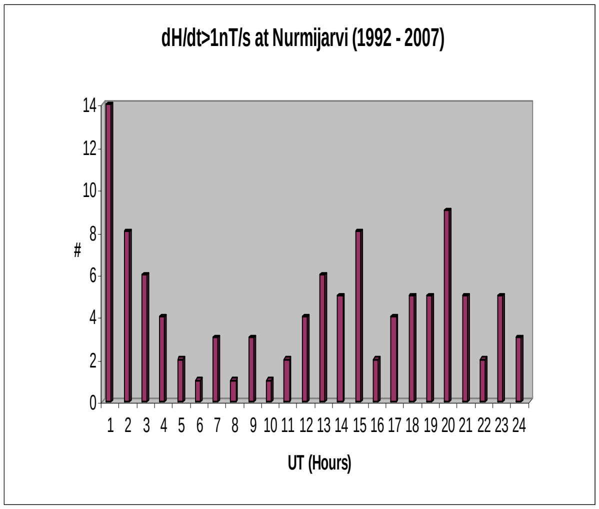
Fig. 4. (a) Distribution of substorms as a function season variations from 1992-2007 at Soroya and Nurmijarvi Observatories. (b) Monthly average of sunspots number from 1992-2007.

coefficient of 0.939 and a coefficient of determination (r^2) of 0.882, which indicates that 88.2% of max dH/dt can be accounted for using the max H, Dst, and max AE indices. At Soroya we found a very good relationship between max dH/dt, max H, Dst and max AE, with a correlation coefficient 0.92 and a coefficient of determination (r^2) of 0.813, which implies that 81.3% of max dH/dt can be accounted for the using max H, minimum value of Dst, and max AE indices.

Boteler *et al*. (1998) concluded that the increasing part of the disturbance has greater time derivatives of the horizontal magnetic field the maximum electric field is in the opposite direction to the electrojet and variation in ground observations of dH/dt may be due to the intensity, location and orientation of the auroral electrojet. GIC are driven by rapid variation of ionospheric currents at high latitude where the most intense GIC are experienced. These variations are thought to be related to the intensification of the electrojet during enhanced ionospheric convection conditions and to the development of the substorm current wedge during geomagnetic storms (Pulkkinen *et al*., 2003; Wintoft, 2005; Weigel *et al*., 2003; Viljanen *et al*., 1999). Viljanen (1997) indicates that ionospheric currents other than east-west auroral electrojets play an important role in the time derivative of the magnetic field and in the electric field at the Earth's surface, and thus also in GIC.

RESULTS AND DISCUSSION

Due to the tilt of the solar rotation axis with respect to the ecliptic plane, the Earth achieves its highest northern (southern) heliographic latitudes in October-November (March and April, respectively), enhancing the fraction of time derivatives of the horizontal geomagnetic field at



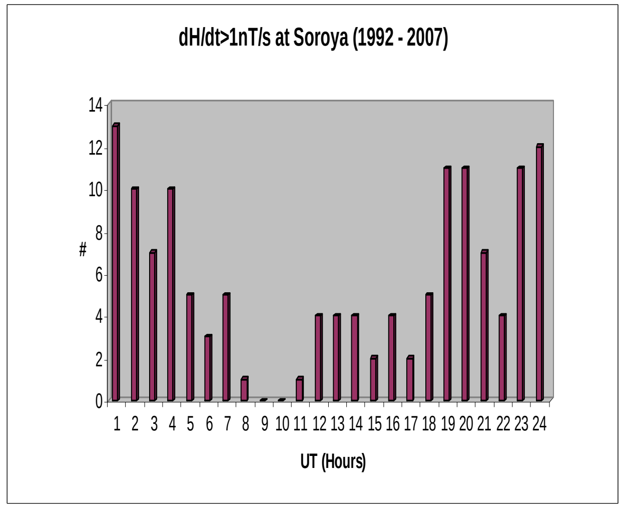


Fig. 5. Hourly variation of number of time steps between 1992–2007 and 1992 -2007 when dH/dt exceeded 1nT/s at two IMAGE magnetometer stations. Soroya is located in the auroral region and Nurmijarvi in the subauroral region.

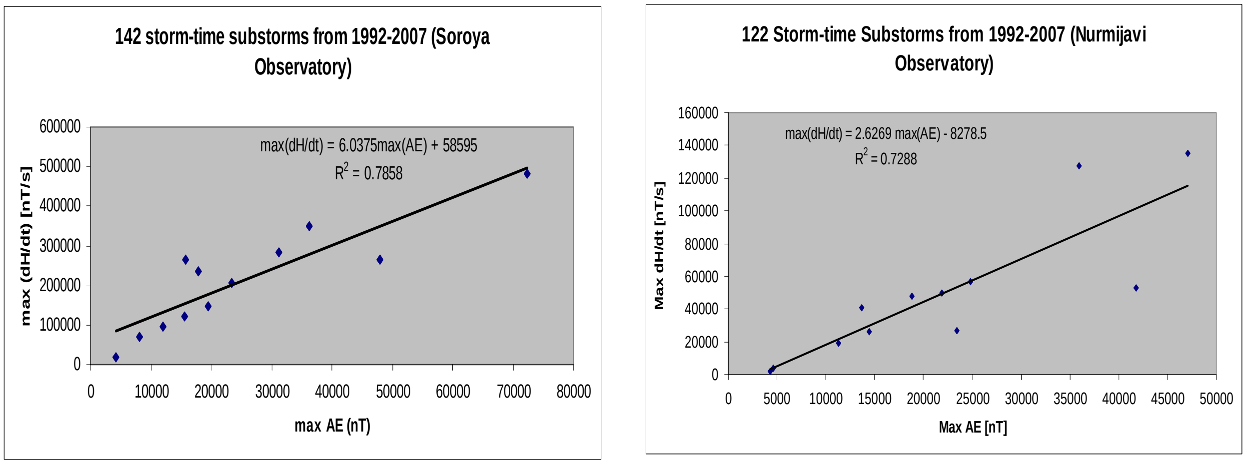
these times. The different effective latitudinal gradients in the solar wind parameters across the heliographic equator in the northern and southern magnetic hemispheres imply a new, persistent north-south asymmetry which is related to the solar magnetic cycle (Mursula *et al*., 2002). There is strong evidence that a related north–south asymmetry has existed in the solar wind even in the mid-19th century, during an earlier period of high solar activity, while the asymmetry has been weak or vanished during the low active cycles at the turn of the 19th and 20th century. Thus, the more active the Sun is, the more asymmetric it is, implying that the solar dynamo itself is north–south asymmetric (Mursula and Zieger, 2001). Mursula (2007) suggested that the quadrupole moment is not only phase locked but also proportional to the dipole moment, leading to a larger (absolute) asymmetry during high activity (Zhao *et al*., 2005).

Time derivatives of the horizontal geomagnetic field of 16.92%, 29.76%, 20.86% and 32.47% of GIC activity (geomagnetically induced current) can be allotted to Winter, Spring, Summer and Autumn respectively in the auroral region, while time derivatives of the horizontal geomagnetic field of about 18.89%, 22.25%, 18.54% and 40.32% of GIC activity can be attributed to Winter, Spring, Summer, and Autumn respectively in the subauroral region. The variations of time derivatives of the horizontal geomagnetic fields measured at the Earth's surface depend on sub-surface electrical conductivity variations and upon the spatial morphology and temporal variability of the source field incident at the Earth–air interface.

The geomagnetic field variation may be due to factors external to the Earth and essentially related to solar activity. This seems to be due to the difference in the neutral winds or to the magnetic effect of the field-aligned current (FAC) flowing between the two hemispheres generated by the asymmetry in the ionospheric dynamo action. The atmospheric motions in the Earth's magnetic field create a natural dynamo with two current cells: one in the sun-lit northern hemisphere flowing counter-clockwise, and the other in the sun-lit southern hemisphere flowing clockwise. In the auroral regions the daily variation, besides being due to the extension of the mid latitude system, is mainly due to FAC flowing along the geomagnetic field lines and connecting the magnetosphere to the ionosphere. The FAC are strongly dependent on the IMF and are believed to be the primary source for the auroral and subauroral regions asymmetry (Cafarella *et al*., 2007).

There is a good correlation between the pairs of max dH/dt and AE index and max H and AE index, which may improve our prediction possibilities. From our results, 72.88% and 80.09% of geomagnetically induced current could be predicted using the max dH/dt and AE index at Nurmijarvi. The scattering may be due to geographical location as suggested by Pulkkinen *et al*. (2001) and Trichentenko and Bottler (2004). We also observed that maximum value of time derivatives of the horizontal geomagnetic field increases from subauroral latitude to auroral latitude and horizontal H intensities also increase from auroral latitude to subauroral latitude. It was suggested that the large variation of geomagnetic field may be due to aurora electrojet and small scale current like vortices (Viljanen, 1997; Viljanen *et al*., 2001, 2006; Apantenkov *et al*., 2004; Pulkkinen *et al*., 2002).

However, the ionospheric dynamo is considered one of the key parameters in the generation of ionospheric current and fields. When the dynamo is disturbed, it produces an ionospheric electric current and an electric field at the high latitude ionosphere during geomagnetic



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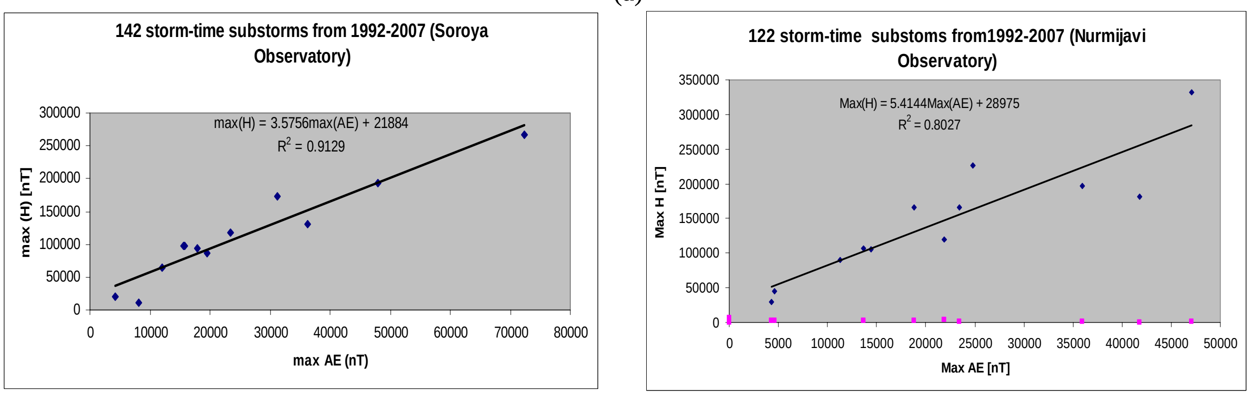

(b)

Fig. 6. The max dH/dt versus AE index (upper panel) and max H versus AE index (lower panel) at two IMAGE magnetometer stations (Soroya and Nurmijarvi). The straight line is the linear regression graph.

storms. The ionospheric current subsequently produces variation in the geomagnetic field at the Earth's surface, as well as geomagnetically induced currents in the ground as an asymmetric component.

CONCLUSION

The greatest GIC problem occurs at high latitudes in auroral and subauroral regions. In these areas geomagnetic disturbances are severe and frequent since the ionospheric source is typically a localized electrojet. In this study we found maximum time derivatives of the horizontal magnetic field statistically significant in October in auroral and subauroral region. Seasonal variations were also seen, Autumn being more geomagnetically active than other seasons. This implies that, the latitudinal dominance of one IMF sector is systematically more strongly developed in the northern heliographic hemisphere irrespective of solar polarity. This means that annually averaged HCS (Heliospheric Current Sheet) is systematically shifted or coned toward the heliographic south at solar minimum times as suggested by Mursular and Hiltula (2003). The coronal holes tend towards the solar mid-latitude during the declining phase of the solar cycle, leading to a strong tilted streamer belt and heliospheric current sheet. During the declining phase and minimum streamer belt is systematically displaced from the equator. However, the Sun with the heliosheet is like a bashful ballerina who is repeatedly trying to push her excessively high flaring skirt downward every 11 years. This implies that the open magnetic field is north-south asymmetric at these periods, suggesting that the solar dynamo has an asymmetric component.

Midnight and early morning are more geomagnetically disturbed than the daytime when both hemispheres of auroral zones are in darkness in Autumn and Spring. The test of correlation was performed between the horizontal time derivatives of geomagnetic field and the measured ionospheric response (AE index) and showed a closer relationship with a high correlation of 0.886 and 0.854 in auroral and subauroral regions respectively. Furthermore, there is strong relationship between max dH/dt, max H, max AE and Dst, with a high correlation coefficient of

0.902 and 0.939 in the auroral and subauroral regions, and this can improve our space weather prediction systems.

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