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Superposed epoch analyses of HILDCAAs and their interplanetary drivers: Solar cycle and seasonal dependences

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ABSTRACT

We study the solar cycle and seasonal dependences of high-intensity, long-duration, continuous AE activity (HILDCAA) events and associated solar wind/interplanetary external drivers for ~$3\frac{1}{2}$ solar cycle period, from 1975 to 2011. 99 HILDCAAs which had simultaneous solar wind/interplanetary data are considered in the present analyses. The peak occurrence frequency of HILDCAAs was found to be in the descending phase of the solar cycle. These events had the strongest time-integrated AE intensities and were coincident with peak occurrences of high-speed solar wind streams. The event initiations were statistically coincident with high-to-slow speed stream interactions, compressions in the solar wind plasma and interplanetary magnetic field (IMF). The latter were corotating interaction regions (CIRs). The signatures of related CIRs were most prominent for the events occurring during the descending and solar minimum phases of the solar cycles. For these events, the solar wind speed increased by ~41% and ~57% across the CIRs, respectively. There was weak or no stream–stream interaction or CIR structure during the ascending and solar maximum phases. HILDCAAs occurring during spring and fall seasons were found to occur preferentially in negative and positive IMF sector regions (toward and away from the Sun), respectively.

1. Introduction

High-intensity, long-duration, continuous AE activity (HILDCAA) events are known to be associated mostly with high-speed solar wind streams (HSSs) (Tsurutani and Gonzalez, 1987; Tsurutani et al., 1995, 2006a; Hajra et al., 2013, 2014a,b). These geoeffective events are distinguished from other types of geomagnetic activity by four strict criteria, as proposed by Tsurutani and Gonzalez (1987): (i) HILDCAAs are defined to be intervals of intense auroral activities characterized by peak AE intensities greater than 1000 nT, (ii) have a minimum of 2 days duration, when (iii) AE values do not drop below 200 nT for more than 2 h at a time. These events are also defined (iv) to occur outside of the main phases of the geomagnetic storms. In general, HILDCAAs are found to be associated with weak ring current enhancements (Dst ≥ -50 nT), recovery phases of geomagnetic storms, or independent of storms. The study of Tsurutani and Gonzalez (1987) reported a one-to-one correspondence of HILDCAAs with interplanetary Alfvén waves (Belcher and Davis, 1971) accompanying the HSSs (Tsurutani et al., 2005, 2006a,b). The auroral activity is attributed to the solar wind energy transfer into the magnetosphere by the continuous, sporadic magnetic reconnection between Earth's magnetopause field and southward component of the interplanetary Alfvén waves (Tsurutani and Gonzalez, 1987; Tsurutani et al., 1995; Hajra et al., 2014a).

A recent study by Hajra et al. (2013) found that HILDCAA events statistically start in the positive gradients of solar wind speed (Vsw) and plasma temperature (Tsw). These were found to be associated with typical signatures of corotating interaction regions (CIRs), high-to-slow speed stream interactions causing solar wind plasma and magnetic field compressions (Smith and Wolfe, 1976; Tsurutani et al., 2006a). The HILDCAA intervals were shown to be well-correlated with the HSS events. On the other hand, there was a small number (6%) of events related to interplanetary coronal mass ejections (ICMEs).

It has been shown (Hajra et al., 2014b) that HILDCAA events are associated with generation of magnetospheric relativistic electron acceleration (Paulikas and Blake, 1979; Baker et al., 1986; Summers et al., 1998; Meredith et al., 2003; Tsurutani et al., 2006a,b; Hajra et al., 2013). The relativistic electrons are known as "killer electrons" for their hazardous effects to orbiting spacecraft (Wrenn, 1995; Horne, 2003). Also, a majority of the solar wind energy input is shown to be dissipated in the outer magnetosphere and ionosphere during HILDCAA events (e.g., Hajra et al., 2014a).

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These make HILDCAA events important aspects of modern space weather studies. The aim of the present study is to investigate the general geomagnetic characteristics of HILDCAAs and associated interplanetary structures. The method of superposed epoch analysis is applied to the events occurring during ~$3\frac{1}{2}$ solar cycles (1975–2011). Although each event has its own distinctive characteristics, we apply a statistical approach in order to identify common elements and patterns. The ultimate goal is to understand the basic physical mechanisms for the HILDCAA events. We also investigate possible solar cycle and seasonal dependences. Although magnetic storms and their solar/interplanetary drivers have been investigated for almost 50 years (e.g., Rostoker and Falthammar, 1967; Gonzalez and Tsurutani, 1987; Gonzalez et al., 1994; Gosling et al., 1990; Huttunen and Koskinen, 2004; Echer et al., 2008; Hutchinson et al., 2011, and references therein), there has been no such study on the solar/interplanetary drivers of HILDCAAs using statistical means to date.

2. Data and method of analysis

As indicated in Section 1, HILDCAA events were identified by four criteria (Tsurutani and Gonzalez, 1987):

(i) the events had peak AE intensities greater than 1000 nT,
(ii) the events had durations at least 2 days in length,
(iii) the high AE activity was continuous throughout the interval, i.e., AE never dropped below 200 nT for more than 2 h at a time, and
(iv) the events occurred outside the main phases of geomagnetic storms.

To identify HILDCAA events, we first detected intervals with AE > 1000 nT. The data were scanned both forward and backward in time to determine where the event decreased below 200 nT for 2 h or more. If this interval was outside of a storm main phase (Dst < −50 nT: Akasofu, 1981; Gonzalez et al., 1994) and was longer than 2 days, this was categorized as a HILDCAA event. Using this methodology, Hajra et al. (2013) developed a list of 133 HILDCAA events occurring during ~$3\frac{1}{2}$ solar cycle period, from 1975 through 2011. The list of the events is available, upon request, for studies of chorus, relativistic electrons, as well as ionospheric and geomagnetic effects. Of the 133 events, 99 had simultaneous geomagnetic and solar wind/interplanetary data available. We study the latter events here. The geomagnetic data (1 h resolution) were obtained from the World Data Centre for Geomagnetism, Kyoto, Japan (http://wdc.kugi.kyoto-u.ac.jp/). The solar wind data (1 min resolution) were obtained from the OMNI website (http://omniweb.gsfc.nasa.gov/). The latter data had been already time-shifted to coincide with solar wind convective times of impingement at the nose of the magnetopause.

To study the solar cycle dependences, the events were separated into four solar cycle phases: the ascending (1977–1978, 1987–1988, 1998–1999, 2011), solar maximum (1979–1981, 1989–1991, 2000–2002), the descending (1982–1984, 1992–1994, 2003–2005), and solar minimum (1975–1976, 1985–1986, 1995–1997, 2006–2010) phases. Annual averaged $F_{10.7}$ solar flux (10^{-22} W m^{-2} Hz^{-1}) data (http://www.drao.nrc.ca/icarus) were used to identify solar cycle phases. The events were also grouped into four (northern hemispheric) seasons defined as follows: spring equinox (February, March, April), summer solstice (May, June, July), fall equinox (August, September, October), and winter solstice (November, December, January).

3. Results

3.1. Solar cycle dependences

In the upper panel of Fig. 1 the histogram shows the occurrence frequency of HILDCAAs (N_H^y) over the interval of study (1975–2011). This is the number of events in a year divided by the number of months when observations were available for that particular year. AE gaps are denoted by a "G". Also shown in the

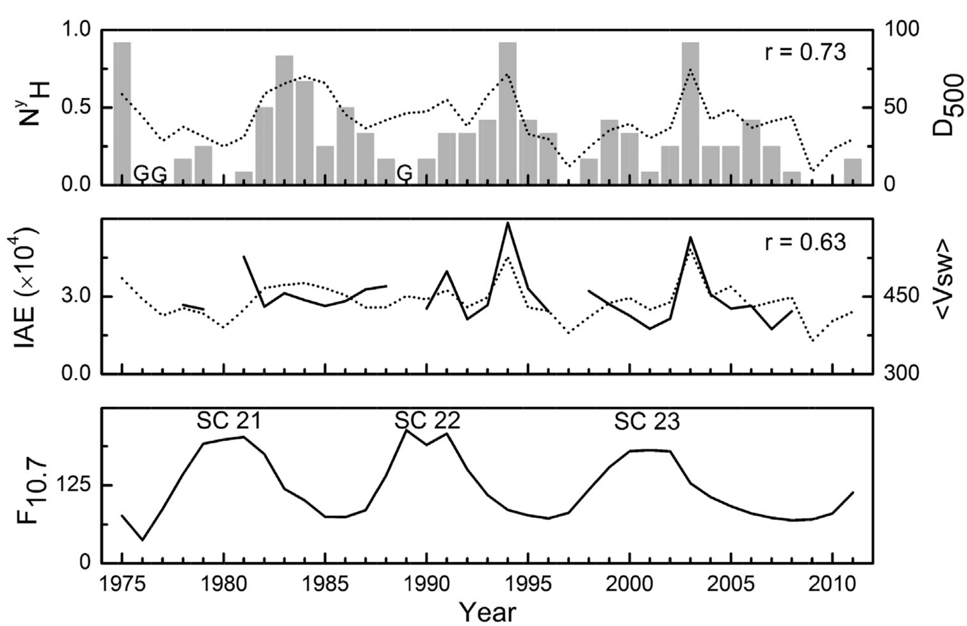

Fig. 1. Histogram (legend on the left) in the top panel gives the yearly HILDCAA numbers (N_H^y) normalized by months of observation. The "G"s represent AE data gaps from January 1976 to December 1977, from July 1988 to February 1989, and from April to December of 1989. The dotted curve (legend on the right) in the same panel shows the yearly mean values of percentage occurrence of HSSs (D_{500} in percentage). In the middle panel, the solid line (legend on the left) shows the time-integrated AE strength (IAE in nT h). The dotted curve (legend on the right) in the middle panel shows the yearly mean solar wind speed (⟨Vsw⟩ in km/s). The linear regression coefficients (r) between N_H^y and D_{500}, and between IAE and ⟨Vsw⟩ are indicated in the upper right of each panel. Both correlations are statistically significant at a > 95% confidence level. The bottom panel shows the variation of yearly mean $F_{10.7}$ solar flux for the entire period of observation. Solar cycles (SCs) are marked in the bottom panel.