

1 **Title:** Solar Cycle Dependence of High-Intensity, Long-Duration, Continuous AE Activity
2 (HILDCAA) Events

3

4 **Running title:** HILDCAAs

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Abstract

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25
26 High-Intensity, Long-duration, Continuous AE Activity (HILDCAA) events are studied using
27 long-term geomagnetic and solar wind/interplanetary databases. We use the strict definition of a
28 HILDCAA event, that it occurs outside of the main phase of a magnetic storm, the peak AE is
29 >1000 nT, and the duration is at least 2 days long. 133 events have been identified from the AE
30 indices in the 1975 to 2011 interval, a $\sim 3\frac{1}{2}$ solar cycle span. Of the 133 events, 99 had
31 simultaneous interplanetary data available. The overwhelming majority (94%) of these latter cases
32 were associated with high-speed solar wind stream (HSS) events. The remaining 6% of the cases
33 occurred after the passage of interplanetary coronal mass ejections (ICMEs). The HSS-related
34 events were typically associated with large interplanetary magnetic field (IMF) B_z variances.
35 The ICME-related events were characterized by steady southward B_z intervals or low frequency
36 fluctuations, both of which we view as possible different interplanetary phenomena. HILDCAA
37 events have been found to have their largest occurrence frequency in the solar cycle descending
38 phase (~ 6.8 /year) with the second largest at solar minimum (~ 3.5 /year). The occurrence
39 frequencies were considerably lower in the ascending phase (~ 2.5 /year) and at solar maximum
40 (~ 2.2 /year). Thus, HILDCAAs can occur during all phases of the solar cycle, with the
41 descending phase ~ 3 times more likely to have an event than at solar maximum and the
42 ascending phase. The HILDCAA events that occurred in the declining phase and at solar
43 minimum were $>20\%$ longer in duration than those in the ascending phase and solar maximum,
44 respectively. The events during the recent solar and geomagnetic minima, 2007-2009, were, on
45 the average, $\sim 17\%$ and 14% weaker in peak AE than the events during the previous two minima
46 of 1995-1997 and 1985-1987, respectively. The recent minimum events were $\sim 35\%$ and 41%

47 shorter in durations, respectively, than the events during those previous minima. The yearly
48 occurrence of the events exhibited statistically significant correlation (>0.70) with yearly average
49 speed and number of HSSs. No seasonal dependence of HILDCAA were noted.

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1. Introduction

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53 It has been shown that continuous, intense auroral activity, called High-Intensity, Long-Duration,
54 Continuous AE Activity (HILDCAA) event [Tsurutani and Gonzalez, 1987] is associated with
55 the generation of magnetospheric relativistic electron acceleration [Paulikas and Blake, 1979;
56 Baker et al., 1986; Summers et al., 1998; Nakamura et al., 2000; Lorentzen et al., 2001;
57 Meredith et al., 2003; Tsurutani et al., 2006a,b]. The scenario posed is that 10-100 keV electrons
58 are injected into the nightside sector of the magnetosphere during impulse substorm and
59 convection events [Horne and Thorne, 1998; Obara et al., 2000; Tsurutani et al., 2006a]. The
60 electrons are heated preferentially in the T_{\perp} direction such that $T_{\perp} > T_{\parallel}$ (T_{\perp} and T_{\parallel} being electron
61 temperatures perpendicular and parallel to the ambient magnetic field, respectively) through the
62 injection process and thus are unstable to the temperature anisotropy instability [Kennel and
63 Petschek, 1966; Tsurutani et al., 1979; Tsurutani and Lakhina, 1997] generating electromagnetic
64 plasma waves called chorus [Gurnett and O'Brien, 1964; Burtis and Helliwell, 1969; Tsurutani
65 and Smith, 1974, 1977; Meredith et al., 2003; Tsurutani et al., 2011a]. Cyclotron resonance
66 between the plasma waves and the electrons leads to pitch angle scattering of the electrons and
67 loss to the ionosphere [Inan et al., 1978; Thorne et al., 2005; Summers et al., 2007; Tsurutani et
68 al., 2009, 2013; Lakhina et al., 2010]. The waves also interact with the electrons by phase-
69 trapping them [Li et al., 1997; Omura et al., 2008], leading to the acceleration of electrons to

70 relativistic energies. It is generally accepted that these continuous, intense auroral activity events
71 are associated with high-speed solar wind streams (HSSs) which emanate from coronal holes
72 [Sheeley *et al.*, 1976; Tsurutani and Gonzalez, 1987; Tsurutani *et al.*, 1995].

73
74 The purpose of this effort is to study HILDCAA events from 1975 to 2011 to determine the solar
75 cycle and seasonal dependences of this phenomenon for the first time. The properties of these
76 events such as the temporal length, and the peak, average and integrated intensities will be
77 characterized. The results of this survey and a list of the events will be available, upon request,
78 for studies of chorus, relativistic electrons, as well as ionospheric and geomagnetic effects.

79

80 **2. Data used and method of analyses**

81

82 **2.1. HILDCAA criteria**

83 In the present study, all HILDCAA events occurring during 1975-2011 were identified when
84 data were available. The events were selected using the following four criteria of *Tsurutani and*
85 *Gonzalez* [1987]:

86

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

92

93 It should be mentioned that the “HILDCAA criteria” originally selected by *Tsurutani and*
94 *Gonzalez* [1987] were stringent in order to minimize the number of events to be studied. The
95 same physical process may occur when one or more of the four criteria are not strictly followed.
96 It was also stressed that the mechanisms creating HILDCAAs must be separate from those
97 creating magnetic storm main phases. It should also be noted that the acronym HILDCAA
98 contains the term “AE activity”, and does not indicate only substorm activity [see *Tsurutani et*
99 *al.*, 2004 and *Guarnieri*, 2006].

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101

2.2. Geomagnetic and interplanetary data

102 To identify HILDCAA events, 1-min AE indices from the World Data Center for
103 Geomagnetism, Kyoto, Japan (<http://wdc.kugi.kyoto-u.ac.jp/>) were used. The Dst indices (1-h
104 time resolution) used to identify geomagnetic storm main phases were obtained from *Echer et al.*
105 [2011a]. Our definition of a magnetic storm main phase was an interval of a decrease in Dst with
106 peak Dst <-50 nT [*Akasofu*, 1981; *Gonzalez et al.*, 1994]. Descriptions of the indices may be
107 found in *Sugiura* [1964], *Davis and Sugiura* [1966] and *Rostoker* [1972]. To identify HILDCAA
108 intervals, AE >1000 nT events were first sought. The data was scanned both forward and
109 backwards in time to determine where the event decreased below 200 nT for 2 h or more. If this
110 event was outside of a storm main phase and the event was longer than 2 days, this was
111 categorized as a HILDCAA event.

112

113 133 events were identified during the study interval. In Figure 1, the distribution of the
114 HILDCAA events is shown as a function of both year and month. The crosses in the figure
115 indicate data gaps.

116
117 Solar wind/interplanetary data at 1-min time resolution were obtained from the OMNI website
118 (<http://omniweb.gsfc.nasa.gov/>). OMNI interplanetary data had been already time-adjusted to
119 take into account the solar wind convection time from the spacecraft to the bow shock, so no
120 further adjustments to the interplanetary data used were made in this study (see
121 http://omniweb.gsfc.nasa.gov/html/omni_min_data.html).

122

123 **2.3. Solar cycle and seasonal dependences**

124 To study the HILDCAA event solar cycle dependence, the events were first separated into
125 individual solar cycles (SCs). They are: SC 21 (1975-1985), SC 22 (1986-1995), SC 23 (1996-
126 2005) and SC 24 (2006-2011). The solar cycles were then divided into four phases, the
127 ascending phase (1977-1978, 1987-1988, 1998-1999, 2011), solar maximum (1979-1981, 1989-
128 1991, 2000-2002), the descending phase (1982-1984, 1992-1994, 2003-2005) and solar
129 minimum (1975-1976, 1985-1986, 1995-1997, 2006-2010). The events were also divided into
130 seasons of the year. The seasons are defined as follows: northern hemisphere spring equinox
131 (February, March, April), summer solstice (May, June, July), fall equinox (August, September,
132 October) and winter solstice (November, December, January).

133

134 Annual averaged $F_{10.7}$ solar flux ($10^{-22}\text{Wm}^{-2}\text{Hz}^{-1}$) data (<http://www.drao.nrc.ca/icarus>) were used
135 to identify solar cycle phases. Although there is little difference in the solar cycle phases between
136 those shown in $F_{10.7}$ and sunspot numbers, it was felt that $F_{10.7}$ was more appropriate [Doherty *et*
137 *al.*, 2000] for a study that involved HSSs emanating from coronal holes.

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2.4. Nested and normalized variances

Nested variances of the interplanetary magnetic field (IMF) components [Tsurutani *et al.*, 1982] were calculated to have a quantitative measure of interplanetary Alfvén wave intensities [Tsurutani *et al.*, 2011a,b; Echer *et al.*, 2011b]. Since interplanetary Alfvén wave fluctuations are more or less isotropic and Bz is an important component leading to geomagnetic activity at Earth [Dungey *et al.*, 1961], only the Bz component variances (σ_z^2) are shown in the paper. The 10-min, 30-min, 1-h and 3-h variances were calculated from 1-min average magnetic field data and then were used to make 3-h averages of those quantities. Because the 3-h values are greater than the 1-h values, 1-h values are greater than the 30-min values (for the same time interval), and so on, the lowest time scale variance is “nested” inside the value of the next higher time scale variance, etc. The scientific benefit of this method of data display is that the variances give the amount of wave power for frequencies up to the variance value. For example, the 3-h average 30-min variance values represent the average wave power occurring in the 1-min (the highest resolution of the data used) to 30-min wave period range. The 1-h variance values give the wave power occurring between 1-min to 1-h wave power range. If one subtracts the 30-min variance value from the 1-h variance value, the resultant value is the amount of wave power which was present for wave periods between 30-min and 1-h. Variances are also easy to calculate and display. They can be used to determine an average wave power and a low-resolution power spectrum.

The variance values were also normalized by dividing the variance values by the square of the magnetic field magnitude (B_0^2). We call these the “normalized variances”, σ_z^2/B_0^2 . This quantity

161 is the most important quantity for cyclotron resonant wave-particle interactions [*Kennel and*
162 *Petschek, 1966; Tsurutani and Lakhina, 1997*].

163

164

3. Results

165

166 Figure 1 shows all of the HILDCAA intervals detected during the interval of study. From the
167 figure, it is seen that HILDCAAs may occur during any month and during any year. There are
168 only a few regions where there are many events. Three intervals stand out from the rest: (i) May-
169 August 1983-1985, (ii) January-May 1993-1995 and (iii) April-October 2002-2003. All three of
170 these intervals are in the declining phases of the solar cycle (more will be stated about this later).
171 However, the seasons are quite different. The first interval is during summer, the second during
172 spring and the third during summer-fall.

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174

3.1. Case studies on HILDCAA events

175 An example of a HILDCAA event and associated solar/interplanetary variations during
176 December 2003 is shown in Figure 2. As denoted by the horizontal dash-dot line in the AE
177 panel, the event started at ~0248 UT on day 343 (9 December), 2003 and continued for ~7 days
178 until ~0402 UT on day 350 (16 December). The peak intensity (AE) of the event was ~1840 nT.
179 This HILDCAA event was preceded by the main phase of a moderate intensity geomagnetic
180 storm ($Dst = -54$ nT). The inspection of the solar wind and interplanetary data indicates that the
181 event occurred during a HSS-interval. The HSS had a peak solar wind speed (V_{sw}) of ~860
182 km/s. It started by the middle of day 342, and persisted until day 350. The solar wind
183 temperature (T_{sw}) more-or-less followed the variation of V_{sw} [*Lopez and Freeman, 1986*].

184

185 Compressions in plasma and magnetic fields at the interface between the HSS and the slow
186 stream in the anti-solar direction (upstream) of the HSS are evident in the increases of plasma
187 density (N_{sw}) and IMF magnitude (B_0). This can be noted from ~ 0309 UT on day 341 to 1522
188 UT on day 343. These signatures identify this as a corotating interaction region (CIR) [*Smith and*
189 *Wolfe*, 1976; *Tsurutani et al.*, 2006a]. For more details of HSS-slow speed stream interactions,
190 we refer the reader to *Hundhausen* [1973] and *Pizzo* [1985].

191

192 During the HILDCAA interval, B_z had an average value of ~ -0.41 nT. In the next to lowermost
193 panel, 3-h averages of 10-min, 30-min, 1-h and 3-h nested variances of B_z are displayed. The
194 bottom panel gives the normalized variances of B_z . As can be observed from the figure, the
195 variance values were enhanced (3-h variance ~ 47 nT², 1-h ~ 39 nT²) near the stream-stream
196 interaction region where the magnetic field was strongly compressed. This result is similar to
197 results of analysis of other HSSs, one occurring in 2003 [*Tsurutani et al.*, 2011a] and another in
198 2008 [*Echer et al.*, 2011b]. During the HSS-interval, the 3-h (1-h) variance ranged from ~ 1.17 to
199 15 nT² (~ 0.92 - 12 nT²), with the average value ~ 7 nT² (5 nT²). The normalized variances were
200 found to be comparable during the stream interaction region and HSS-interval. The peak,
201 minimum and average values of 3-h (1-h) normalized variances were $\sim 3.4 \times 10^{-1}$, 1.8×10^{-2} and
202 1.5×10^{-1} (0.3×10^{-1} , 1.8×10^{-2} , 1.2×10^{-1}), respectively.

203

204 Figure 3 shows another example of a HILDCAA event during May 2005. The Dst intensity
205 indicates the presence of an intense geomagnetic storm ($Dst = -263$ nT) during the first half of
206 day 135 (15 May), 2005. The recovery phase started at ~ 0900 UT on this day. The intense storm

207 was caused by the southward IMF Bz of the magnetic cloud (MC)/interplanetary coronal mass
208 ejection (ICME) [Klein and Burlaga, 1982; Tsurutani et al., 1988; Echer et al., 2008]. The IMF
209 Bz was intensely southward (~ -45 nT) for more than 3 h. The situation was favorable for the
210 development of the superintense storm main phase [Tsurutani et al., 1992; Echer et al., 2008]. A
211 peak solar wind speed (V_{sw}) of ~ 980 km/s was detected during the main phase of the storm. The
212 variation of the AE index during the storm recovery phase indicates the presence of a HILDCAA
213 from ~ 1708 UT on day 135 (15 May) to ~ 1603 UT on day 138 (18 May). The peak (AE)
214 intensity was ~ 1870 nT.

215
216 The IMF Bz variation during the HILDCAA interval (marked by box) is shown amplified for
217 better viewing. Bz exhibited a small, continuous southward component (average ~ -2.8 nT). The
218 low frequency southward component is associated with the HILDCAA. The two lowermost
219 panels show the nested and normalized variances of Bz for the whole interval. The variances
220 were intense during the storm main phase (peak 3-h variance ~ 174 nT², 1-h ~ 78 nT²). During the
221 HILDCAA-interval, the 3-h (1-h) variance varied from ~ 0.09 to 6.81 nT² (~ 0.07 - 3.56 nT²), with
222 an average value of ~ 1.71 nT² (0.87 nT²). The peak, minimum and average values of 3-h (1-h)
223 normalized variances were 6.3×10^{-2} , 1.4×10^{-3} and 1.9×10^{-2} (2.9×10^{-2} , 0.96×10^{-3} , 0.96×10^{-2}),
224 respectively. These variance and normalized variance values were considerably smaller than
225 those for event 1 (Figure 2).

226
227 From the case studies we found that while the HSS-related event (Figure 2) was associated with
228 large amplitude Bz variances, the ICME-related event (Figure 3) was characterized by small,
229 steady southward IMF Bz intervals or low frequency fluctuations. We view this as a possible

230 different interplanetary mechanism for the geomagnetic activity/HILDCAA. There were 99
231 HILDCAA events where interplanetary data were available. It was found that 93 of the events
232 (94%) were associated with CIRs/HSSs. Only 6 events occurred after the passage of ICMEs. The
233 peak 3-h variances for the 93 CIR-events ranged from ~ 5.1 to 130 nT^2 , with an average value of
234 34 nT^2 . On the other hand, the peak 3-h variance for the 6 ICME-related events varied between
235 ~ 2.41 and 45.4 nT^2 , with average value of 15.3 nT^2 . Thus, the IMF Bz variances for the CIR-
236 related events were larger than those for the ICME-events. We note however a lack of a
237 significantly large database to draw statistical conclusions.

238

239

3.2. Superposed epoch analyses

240 Superposed epoch analyses were performed on the geomagnetic and solar/interplanetary
241 variations for the 93 events associated with HSS/CIR events. The initiation times of HILDCAA
242 events were taken as the zero epoch time. Figure 4 depicts the superposed mean variations and
243 standard deviations of Vsw, Nsw, Tsw, IMF Bo, Bz, Dst and AE indices. The variations of the
244 parameters from 2 days prior to 3 days after the start time of HILDCAAs are shown. The
245 superposed variations may give some qualitative idea about the general features of geomagnetic
246 activity and causative interplanetary variations during HILDCAA events.

247

248 The variations of solar/interplanetary data show typical interplanetary signatures of CIRs (as was
249 illustrated for event 1, Figure 2). The interaction between a HSS and an upstream (anti-
250 sunwardly located) slow-speed stream is evident in the increase ($\sim 48\%$) of average Vsw around
251 zero epoch time. An increase of $\sim 118\%$ was noted in Tsw around the stream interface location. A
252 compression in plasma and magnetic field was evident in the increases of Nsw ($\sim 38\%$) and of Bo

253 (~42%) from ~14 h prior to 18 h after the zero epoch time. The enhanced Tsw and Bo on the
254 right side of the zero epoch time represent the compressed fast stream. On the left side of the
255 zero epoch time, there is a mixture of two effects affecting the plasma and fields. There is a
256 compression of the slow solar wind leading to higher plasma densities, temperatures and
257 magnetic fields. There are also naturally occurring high plasma densities near the heliospheric
258 current sheet (HCS) [Smith *et al.*, 1978; Tsurutani *et al.*, 1995], called the heliospheric plasma
259 sheet (HPS: Winterhalter *et al.* [1994]). A superposed epoch analysis of this type mixes these
260 different physical phenomena.

261
262 Some noteworthy features in Figure 4 are: (i) before event initiation, the average Bz value was
263 ~0 nT; (ii) Bz showed northward-to-southward turning ~2.5 h prior to the event initiation; and
264 (iii) Bz remained negative, though with very small peak values (~-2.4 nT), during the event
265 interval. The northward-to-southward turning may represent the typical HCS crossing or sector
266 reversal of the IMF occurring prior to stream interaction [Smith *et al.*, 1978]. The Bz ~0 nT prior
267 to zero epoch was related to the “magnetic calm” [Tsurutani *et al.*, 1995, 2006a,b; Borovsky and
268 Steinberg, 2006] as evident in low values of Dst (>-20 nT) and AE (~300 nT). Although we
269 observed high frequency fluctuations between northward and southward directions in Bz during
270 individual HILDCAA events (see Figure 2), the superposed variation (average) showed only
271 nearly constant southward values. This result is related to the averaging process of large
272 fluctuations over many events. This superposed southward component of Bz after the sector
273 reversal facilitated the magnetospheric reconnection mechanism [Dungey, 1961; Gonzalez and
274 Mozer, 1974] and is consistent with weak but sustained geomagnetic activity observed in the AE
275 (average value~450-500 nT) and Dst (<-30 nT) variations.

276

277 In the following sections, results of the statistical study on the solar cycle and seasonal
278 dependences as well as the geomagnetic characteristics of HILDCAAs are presented.

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280

3.3. Solar cycle dependences of HILDCAAs

281 We investigate the solar cycle dependence of 133 HILDCAA events by first identifying the
282 months and years of occurrences. The number of events during each year was divided by the
283 number of months of observation in that year (Figure 5). This process corrects the distribution
284 for data gaps. HILDCAA events were found to be distributed primarily around the declining
285 phase and solar minimum. The highest peak occurrences were noted during the declining phase
286 of the solar cycle. Averaging over the solar cycles, it was observed that the occurrence rate of
287 events during the declining phase was $\sim 6.8/\text{year}$. The next most frequent event occurrence
288 happened at solar minimum ($\sim 3.5/\text{year}$). HILDCAA events also occurred at solar maximum
289 ($\sim 2.2/\text{year}$) and in the ascending phase ($\sim 2.5/\text{year}$). Thus, HILDCAAs occurred in all phases of
290 the solar cycle. During the declining phase, the occurrence rate was ~ 3 times as likely as during
291 solar maximum and in the ascending phase.

292

293 Interesting differences between the solar cycles were noted. Around the transition between the
294 SCs 21 and 22, a two-peak nature of HILDCAA occurrence was evident. However, only one
295 peak was noted for the SCs 22-23 transition. Although, two peaks were observed in the
296 descending phase of SC 23, the events were found to be more evenly distributed throughout this
297 cycle.

298

299 The solar cycle dependence of HILDCAAs depicted here is different from the reported solar
300 cycle dependence of intense ($Dst < -100$ nT) geomagnetic storms [*Gonzalez et al.*, 1990, 1994,
301 2007; *Alves et al.*, 2006; *Tsurutani et al.*, 2006a; *Echer et al.*, 2008, 2011a, 2013; *Chakraborty*
302 *and Hajra*, 2010; *Hajra*, 2011]. The largest occurrence of the storms is at and around solar
303 maximum. The minimum occurrence of storms is at solar cycle minimum phase.

304
305 At solar maximum and a few years after solar maximum, the main features present at the Sun are
306 sunspots and active regions. Intense solar flares and coronal mass ejections (CMEs) [*Burlaga et*
307 *al.*, 1981; *Klein and Burlaga*, 1982; *Gosling et al.*, 1990] often occur together because they are
308 both products of solar magnetic reconnection. If this ICMEs have southward B_z components and
309 they hit the Earth's magnetosphere, they cause magnetic storms. At solar maximum ICMEs are
310 known to be the main causes of geomagnetic storms [*Tsurutani et al.*, 1988; *Gosling et al.*, 1990;
311 *Richardson et al.*, 2002; *Echer et al.*, 2008]. The yearly number of CMEs, yearly peak and
312 average CME speeds are reported to exhibit an ~11-year solar cycle variation [*Webb and*
313 *Howard*, 1994; *Gopalswamy et al.*, 2004; *Obridko et al.*, 2012] similar to that of intense
314 geomagnetic storms [*Tsurutani et al.*, 2006a].

315
316 During the declining phase and solar minimum, coronal holes extend to lower solar latitudes and
317 expand in size, becoming the dominant solar feature causing geomagnetic activity. HSSs
318 emanate from these coronal holes [*Krieger et al.*, 1973; *Sheeley et al.*, 1976; *Tsurutani et al.*,
319 1995]. CIRs are formed at the leading edges of the fast streams due to interaction with slow
320 background streams [*Smith and Wolfe*, 1976; *Pizzo*, 1985; *Balogh et al.*, 1999]. CIRs usually
321 lead to moderate magnetic storms ($Dst > -100$ nT: *Tsurutani and Gonzalez* [1997]) and the

322 trailing HSS proper causes prolonged periods of geomagnetic activity [*Tsurutani et al.*, 1995;
323 *Guarnieri et al.*, 2006; *Kozyra et al.*, 2006; *Turner et al.*, 2006]. The HSS/HILDCAA intervals
324 appear as a “recovery phase” of the CIR storm, but in actuality there is fresh input of solar wind
325 energy in addition to the ring current decay [*Tsurutani et al.*, 2004; *Guarnieri*, 2006]. Thus, the
326 HILDCAA solar cycle distribution follows the low latitude coronal hole distribution at the Sun
327 and the CIR/HSS distribution in the solar wind in the ecliptic plane.

328

329 **3.4. Seasonal dependences of HILDCAAs**

330 To study the seasonal dependences, the number of events in a month was divided by the number
331 of years where observations were available for that particular month. Figure 6 shows the
332 HILDCAA distributions during different months of varying solar cycle phases. From the
333 distribution, it is noted that HILDCAAs exhibited no “classical” semiannual seasonal distribution
334 like that for geomagnetic storms [*Clua de Gonzalez et al.*, 1993; *Gonzalez et al.*, 1999; *Echer et*
335 *al.*, 2011a]. There were, however, minor seasonal features, which we mention below. There were
336 lesser occurrences during the month of November. This feature was present for all phases of the
337 solar cycle. During solar maxima and the descending phases, the occurrence rate of solstice
338 events appeared to increase slightly. An overall increase in the number of events during the
339 descending phases compared to those during the ascending phases was prominent. Even and odd
340 solar cycle data were grouped together to maintain consistent solar magnetic field polarities (not
341 shown). No clear semiannual or seasonal dependences were noted. The results are in agreement
342 with the *Mursula et al.* [2011] conclusion, although using a different approach, of ionospheric
343 conductivity control on geomagnetic activity.

344

3.5. Association of HILDCAAs with HSSs

345
 346 Figures 7-8 show the HILDCAA event relationship with HSS properties. In Figure 7, the yearly
 347 peak (V_{sw_p}) and average ($\langle V_{sw} \rangle$) values of solar wind speed (V_{sw}), and the percentage of
 348 days (D_{500}) with HSSs ($V_{sw} \geq 500$ km/s) are compared with yearly occurrences of HILDCAAs
 349 (number per month in each year). The peaks in $\langle V_{sw} \rangle$ and D_{500} coincided strongly with the
 350 yearly peak occurrences of HILDCAAs, while HILDCAAs did not follow the variation of
 351 V_{sw_p} .

352
 353 Figure 8 shows the variations of yearly occurrences of HILDCAAs with yearly values of V_{sw_p} ,
 354 $\langle V_{sw} \rangle$ and D_{500} . HILDCAA occurrence was strongly correlated to $\langle V_{sw} \rangle$ and D_{500} , and had its
 355 poorest correlation with V_{sw_p} . Based on the analysis, we obtained the following relations for
 356 HILDCAA occurrence rate:

357
 358
$$H = (-2.6 \pm 0.4) + (65.5 \pm 9.4) \times 10^{-4} \langle V_{sw} \rangle \quad (r = 0.79) \quad (1)$$

359
$$H = (-0.2 \pm 0.1) + (1.3 \pm 0.2) \times 10^{-2} D_{500} \quad (r = 0.73) \quad (2)$$

360
 361 Here H represents the number of HILDCAAs per month in each year. The relationships are
 362 statistically significant with high correlation coefficients (r). r is 0.79 in equation (1) (correlation
 363 with V_{sw}) and 0.73 in equation (2) (with D_{500}).

364
 365 Higher values of $\langle V_{sw} \rangle$ and D_{500} may indicate yearly dominance of long-lasting corotating
 366 HSSs. The HSSs are accompanied by large-amplitude, non-linear, long-duration Alfvén wave
 367 trains [*Belcher and Davis, 1971; Tsurutani et al., 2005, 2006a,b*]. A particular good example of

368 this is the HSSs that occurred in 1973-1975 [Tsurutani *et al.*, 1995]. It should be mentioned that
369 such strong HSS activity that occurred in 1973-1975 has never happened again. The
370 magnetospheric reconnection between southward components of Alfvénic IMF and the Earth's
371 magnetic field causes continuous energy injection leading to long-sustained high intensity
372 auroral activities or HILDCAAs [Tsurutani and Gonzalez, 1987; Tsurutani *et al.*, 1990, 1995;
373 Gonzalez *et al.*, 2006].

374

375 **3.6. Characteristics of HILDCAAs**

376 We identified different characteristics of each HILDCAA event: (i) the time-integrated AE value
377 throughout the event (IAE), (ii) the average AE value during the event ($\langle \text{AE} \rangle$), (iii) the peak AE
378 value for the event (AE_p), and (iv) the duration of the event (D). Figure 9 shows the relative
379 distributions (histograms) of the events with respect to the characteristic parameters for the entire
380 years of study (1975-2011). The results are summarized in Table 1. IAE varied between 1.4×10^4
381 and 16×10^4 nT-h with an average value of 3.3×10^4 nT-h. About 50% of the events exhibited IAE
382 values in the range of $2-3 \times 10^4$ nT-h and the number of events decreased gradually for larger
383 values of IAE. The $\langle \text{AE} \rangle$ for the events varied in the range of 285-621 nT, with an average
384 value of 422 nT. The majority of the events were characterized by $\langle \text{AE} \rangle \sim 350-500$ nT. The
385 HILDCAAs exhibited peak strengths (AE_p) varying from 1041 to 2155 nT with an average
386 value of 1478 nT. More than 50% of the events had an AE_p in the range of 1200-1600 nT. The
387 duration (D) of HILDCAAs was found to vary from a minimum of ~ 2 days (by definition) to
388 more than 12 days (297 h). The average duration was 3.2 days (~ 76 h). The majority of the
389 events ($\sim 60\%$) had 2 to 3 days (50-70 h) durations.

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3.7. Solar cycle phase dependences of HILDCAA characteristics

391 The HILDCAA events were separated according to their occurrences during different phases of
392 the solar cycle. The solar cycle phase dependences of the HILDCAA characteristics are
393 summarized in Table 2. The events occurring during solar minimum were, on the average, ~29%
394 longer than those during solar maximum. Similarly, the events occurring during the descending
395 phase were ~21% longer than those during the ascending phase.

397
398 During the descending and solar minimum phases, HILDCAAs exhibited appreciably larger
399 ranges as well as average values of IAE, AE_p and D than during the ascending phase and solar
400 maximum, respectively. On the other hand, the <AE> for the events during solar maximum was
401 found to be comparable or even little larger than that during solar minimum. In general, the
402 combined descending phase and solar minimum had comparatively more intense events than
403 solar maximum and the ascending phases.

404
405 One hypothesis to explain this is that during the descending and solar minima phases, polar and
406 low latitude equatorial coronal holes are larger and the HSSs emanating from them are more
407 geoeffective. By the latter, we mean that the center of the HSSs where the speeds are ~750 to
408 800 km/s and the magnetic field variability $\Delta B/B_0$ is ~1 to 2 impinge on the magnetosphere (ΔB
409 being the peak-to-peak amplitude of the transverse magnetic field). These solar wind features
410 cause more intense and longer duration HILDCAA events.

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414 **3.8. Comparison of HILDCAA characteristics between solar and geomagnetic minima**

415 The years 1986, 1996 and 2008 represent three consecutive solar activity minima with yearly
416 mean $F_{10.7}$ values of ~ 74 , 72 and 69, respectively. We have considered the events occurring
417 during solar minimum \pm one year for comparative study (Table 3). Thus since geomagnetic
418 minimum typically occurs ~ 1 year after solar minimum [Echer *et al.*, 2011a; Tsurutani *et al.*,
419 2011b], this includes geomagnetic minimum as well. The numbers of intense AE events during
420 the intervals were 13, 9 and 4, respectively. We intercompared possible differences in the
421 characteristics of HILDCAAs among these solar minima, though it should be noted that the
422 numbers of events are small for any statistical analysis. The events occurring during the recent
423 minimum (2007-2009) were found to be appreciably weaker (AE_p $\sim 17\%$ and 14% lower) and
424 short-duration (D $\sim 35\%$ and 41% shorter) compared to the previous minima (1995-1997 and
425 1985-1987, respectively).

426
427 This result is consistent with the overall lower geomagnetic activity around the recent solar
428 minimum. For the 2008-2009 interval, the IMF Bz variances were examined by Tsurutani *et al.*
429 [2011b] and Echer *et al.* [2011b] and it was shown that not only was the solar wind speed lower,
430 but the IMF Bz variances were lower as well. Other possible causes behind the weak
431 geomagnetic activity around the recent solar minimum are: (i) the low number of equatorial and
432 low-latitude coronal holes, (ii) low IMF magnitudes, (iii) low solar wind speeds, (iv) weakness
433 of magnetohydrodynamic forces in the solar wind and (v) low energy transfer from solar wind to
434 the magnetosphere during the period [de Toma, 2010, 2012; Tsurutani *et al.*, 2011b; Echer *et al.*,
435 2012].

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4. Summary

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This paper presented, for the first time, the results of the statistical studies on the HILDCAAs using long-term (1975-2011) geomagnetic and solar wind/interplanetary databases. The results may be summarized as follows:

- (1) 133 AE events satisfying the “HILDCAA criteria” suggested by *Tsurutani and Gonzalez* [1987] have been identified from 1975 to 2011, a $3\frac{1}{2}$ solar cycle span (Figure 1). A list of events will be made available to people on request.
- (2) Of the 133 events, 99 had simultaneous interplanetary data available. 94% of these cases were associated with interplanetary HSSs. The remaining 6% of the cases occurred after the passage of ICMEs. The HSS-related HILDCAAs were typically associated with large amplitude IMF Bz variances. The ICME-related events were characterized by small, steady southward Bz intervals or low frequency fluctuations (Figures 2, 3).
- (3) The solar cycle variation of HILDCAAs showed an occurrence peak ($\sim 6.8/\text{year}$) during the declining phase. An appreciable number of events were also observed during solar minimum ($\sim 3.5/\text{year}$). The occurrence frequencies were considerably lower in the ascending phase ($\sim 2.5/\text{year}$) and at solar maximum ($\sim 2.2/\text{year}$). Thus, HILDCAAs occurred during all four phases of the solar cycle, with those occurring during declining phases having a ~ 3 times greater probability than those in solar maximum and rising phase (Figure 5).
- (4) The HILDCAA events occurring during the descending phases were, on the average, $\sim 21\%$ longer in duration than those during the ascending phases. Similarly, the solar

460 minimum events were ~29% longer than the solar maximum events. Also, the events
461 during the descending phase and solar minimum were more intense than those during the
462 ascending phase and solar maximum, respectively (Table 2).

463 (5) The events occurring during the most recent solar minimum years (2007-2009) were
464 found to be fewer in number, ~17%, and 14% weaker in strength than those during
465 previous solar minima of 1995-1997 and 1985-1987, respectively (Table 3). Also, the
466 duration of the recent events were ~35% and 41% shorter than those of the two previous
467 minima, respectively. Although the numbers of events during the intervals were small for
468 any statistical analysis, the result is consistent with the overall lower geomagnetic activity
469 around the recent solar minimum [*de Toma*, 2010, 2012; *Echer et al.*, 2011b, 2012;
470 *Tsurutani et al.*, 2011b].

471 (6) The peaks of the solar cycle variation of HILDCAAs were well-correlated with the yearly
472 average V_{sw} and number of days with HSSs ($V_{sw} \geq 500$ km/s) (Figures 7-8). This result
473 is consistent with item (4).

474 (7) HILDCAA distributions did not exhibit any “classical” semiannual variations as observed
475 for geomagnetic storms (Figure 6). During solar maximum, the number of events seemed
476 to be larger during summer compared to equinoxes. The occurrences were consistently
477 low during the month of November in all phases of the solar cycle. There were no
478 seasonal dependences found. The results may suggest the effect of ionospheric ionization
479 on the magnetic activities [*Mursula et al.*, 2011].

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5. Final comments

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485 This study was done primarily to identify the solar cycle dependences of HILDCAA intervals
486 and to form a database which could be used by investigators for the study of related phenomena.
487 What was not covered in this paper is what HILDCAAs are from a physical viewpoint. This is
488 clearly an important topic but beyond the scope of the present work. The justification for the
489 name “HILDCAA” is given in *Tsurutani et al.* [2011a]. Notice that the word “substorm” is not
490 included in this name (only AE activity), for good reason. Although there are substorms during
491 HILDCAA intervals [*Tsurutani et al.*, 2004], there is clearly much more happening in the
492 magnetosphere/ionosphere system [*Guarnieri*, 2006; *Guarnieri et al.*, 2006]. We encourage the
493 interested reader to pursue this topic.

494
495 The high IMF Bz variances and normalized variances during HILDCAA events most likely
496 indicate interplanetary Alfvén waves that have been shown and discussed in many previous
497 works [*Tsurutani et al.*, 1982, 1990, 2011a,b; *Tsurutani and Gonzalez*, 1987; *Echer et al.*,
498 2011b]. They were not identified as such here because this was not the main focus of this paper.

499
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508 **References**

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747 **Figure captions**

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749 **Figure 1.** The number of HILDCAAs for different months of the years 1975-2011. The values of
 750 different shadings are given in the legend at the right. The crosses represent data gaps from
 751 January 1976 to December 1977, from July 1988 to February 1989, and from April to December
 752 of 1989.

753

754 **Figure 2.** Solar wind/interplanetary parameters and geomagnetic activity indices for a
 755 HILDCAA event during December 2003. From top to bottom, the panels show the variations of
 756 solar wind speed (V_{sw} in km/s), plasma density (N_{sw} in cm^{-3}), temperature (T_{sw} in K), IMF
 757 magnitude (B_0 in nT), and B_x (nT), B_y (nT), B_z (nT) components in the GSM coordinate
 758 system, and the Dst (nT), AE (nT) indices, respectively. The bottom two panels show the nested
 759 10-min, 30-min, 1-h and 3-h variances (σ_z^2 in nT^2) and normalized variances (σ_z^2/B_0^2) of B_z .
 760 The legend for the variances and normalized variances is given in the next to last panel. The
 761 variances are estimated using 1-min IMF data. In the AE panel, the horizontal dash-dot line
 762 indicates the time interval of the HILDCAA event. There are high amplitude Alfvén waves in
 763 IMF B_z during the HILDCAA interval. This event was caused by the southward components of
 764 the IMF Alfvén waves in a CIR/HSS.

765

766 **Figure 3.** Another example of HILDCAA event but associated with a ICME. The event occurred
 767 during May 2005. The format is the same as in Figure 2. This HILDCAA follows a magnetic
 768 cloud (MC). Note that the IMF B_z during the HILDCAA-interval (marked by box in B_z panel)
 769 are shown in enhanced scale to make clear viewing. The IMF B_z value is slightly negative

770 throughout the entire HILDCAA interval. It is generally devoid of Alfvén waves, unlike the case
 771 shown in Figure 2.

772

773 **Figure 4.** Superposed epoch analyses results for 93 HILDCAA events associated with HSS/CIR
 774 events showing, from top to bottom panels, V_{sw} (km/s), N_{sw} (cm^{-3}), T_{sw} (K), IMF B_o (nT), B_z
 775 (nT), D_{st} (nT) and AE (nT). The solid lines are the mean values and vertical bars represent the
 776 standard deviations. The zero epoch time corresponds to the starting time of the events.

777

778 **Figure 5.** Histograms give the relative occurrence of HILDCAAs during different years of
 779 observations (1975-2011) (see text for details). The continuous line (secondary Y-axis, legend on
 780 the right) shows the yearly smoothed $F_{10.7}$ solar flux. “G” represents data gap. No AE data was
 781 available for the years 1976 and 1977. For the year 1988, AE data was only available from
 782 January to June, and for the year 1989, AE data was available only for the month of March.

783

784 **Figure 6.** Histograms show the relative occurrence of HILDCAAs during each month. From top
 785 to bottom, the panels show the results during the ascending phase, solar maximum, the
 786 descending phase, solar minimum, and during the entire period of observation, respectively. The
 787 numbers in the parentheses represent the total number of events during each interval.

788

789 **Figure 7.** Histograms showing the relative occurrence of HILDCAAs during different years of
 790 observation (1975-2011). The continuous lines (secondary Y-axis, legend on the right) present
 791 the yearly peak (V_{sw_p}) and yearly average ($\langle V_{sw} \rangle$) of solar wind speed and the percentage of
 792 days (D_{500}) with $V_{sw} \geq 500$ km/s. “G” represents data gap.

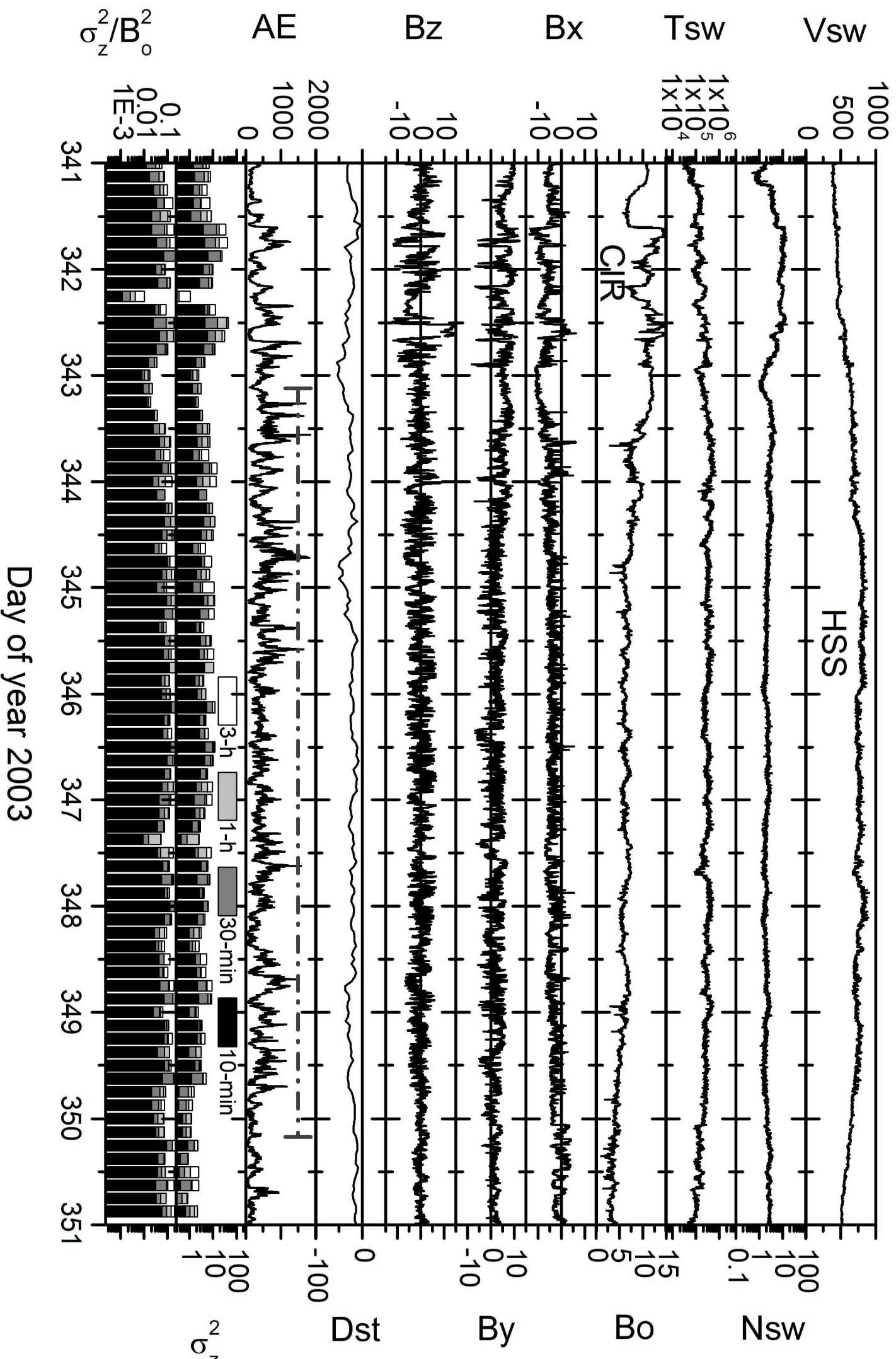
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794 **Figure 8.** The scatter plots showing the relative occurrences of HILDCAAs during each year
795 versus V_{sw_p} , $\langle V_{sw} \rangle$ and D_{500} . The linear regression curves and the corresponding correlation
796 coefficients (r) are also given.

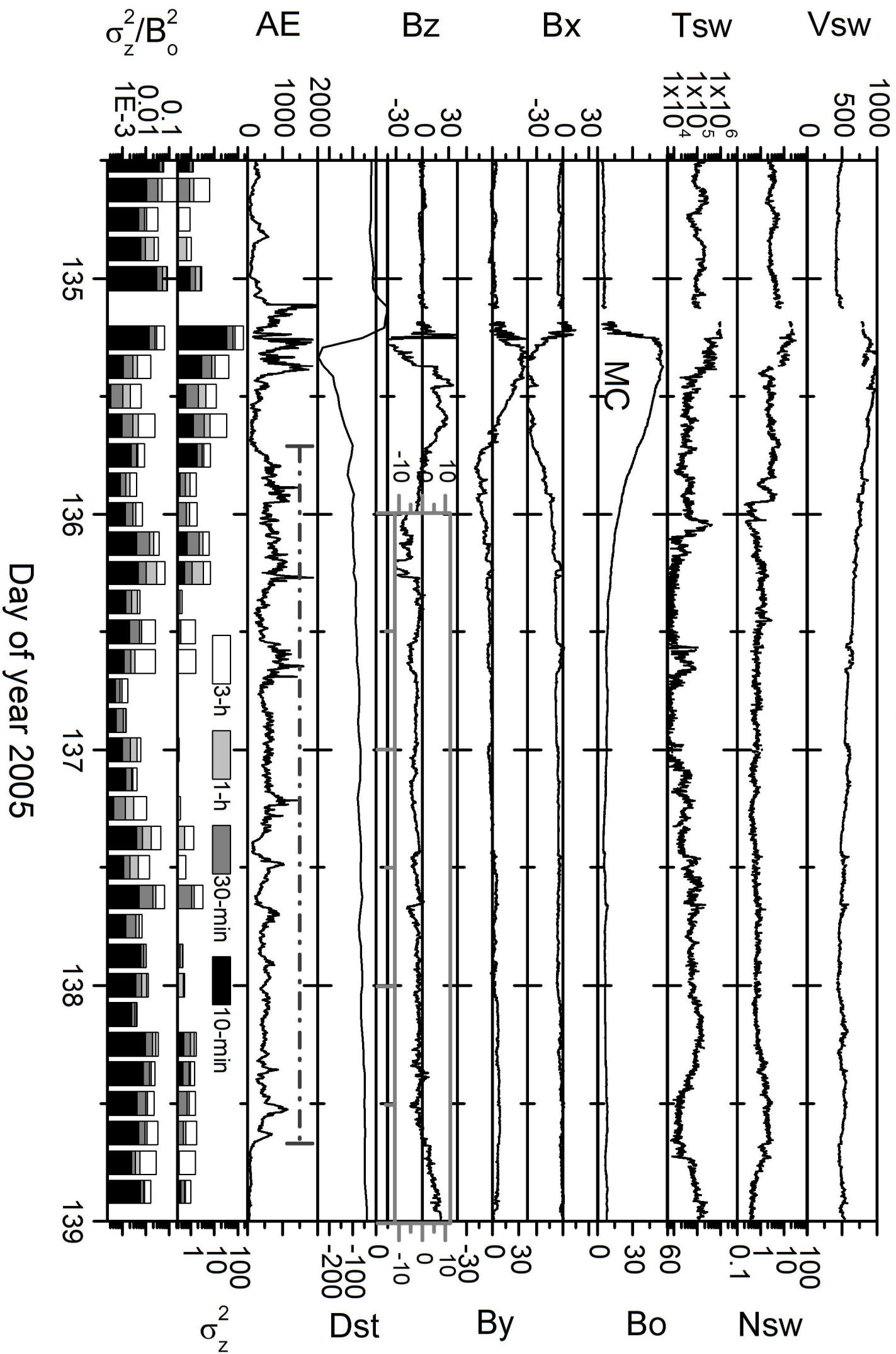
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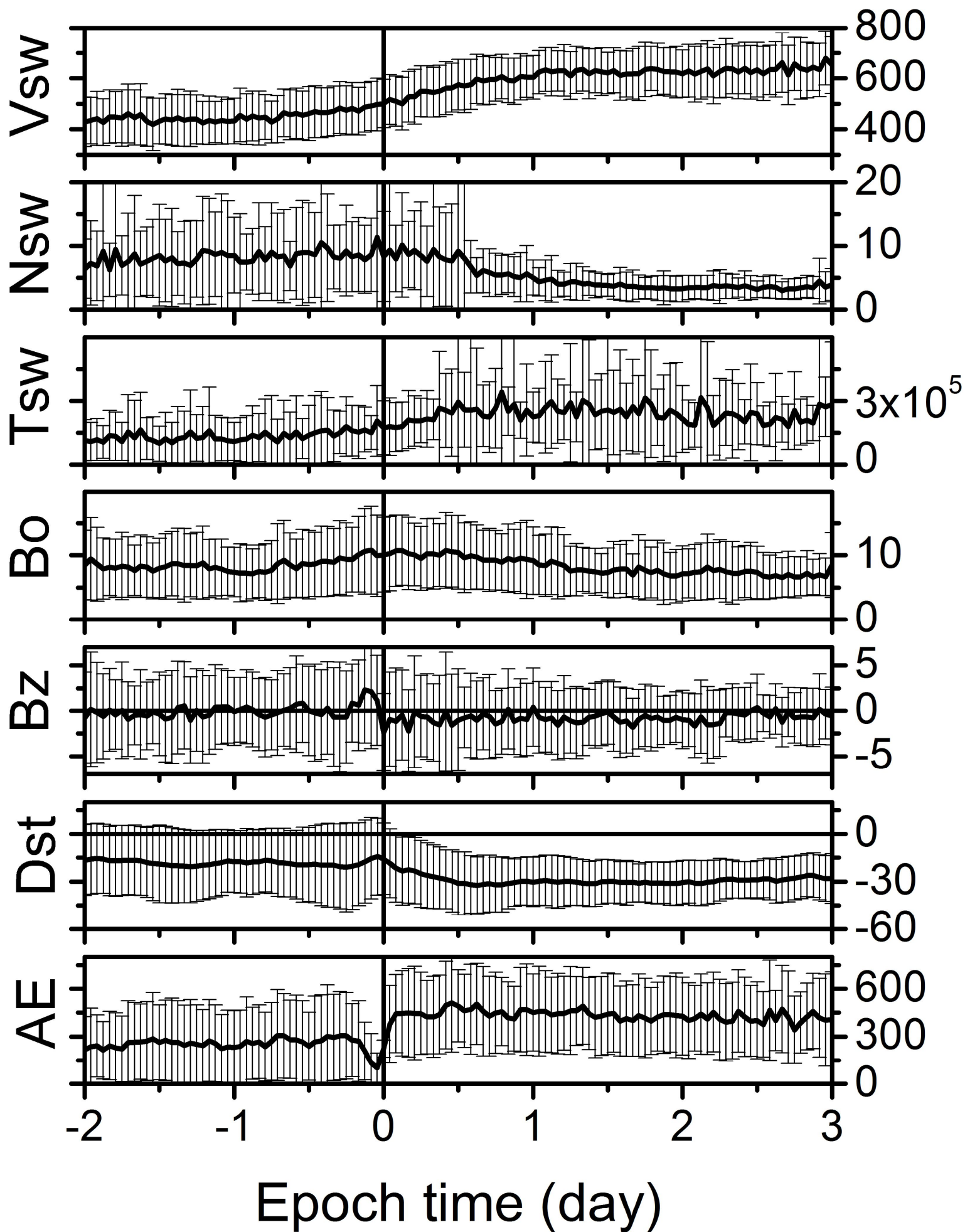
798 **Figure 9.** Histograms of HILDCAAs for different ranges of (a) IAE (10^4 nT-h), (b) $\langle AE \rangle$ (nT),
799 (c) AE_p (nT), and (d) D (h). These histograms are for the 133 events occurring during entire
800 period of observation (1975-2011). The downward arrows in each panel indicate the
801 corresponding average (solid) and median (dotted) values. The lower limits of the parameters
802 are: $D > 48$ h, $AE_p > 1000$ nT, $\langle AE \rangle > 200$ nT. These were by definition.

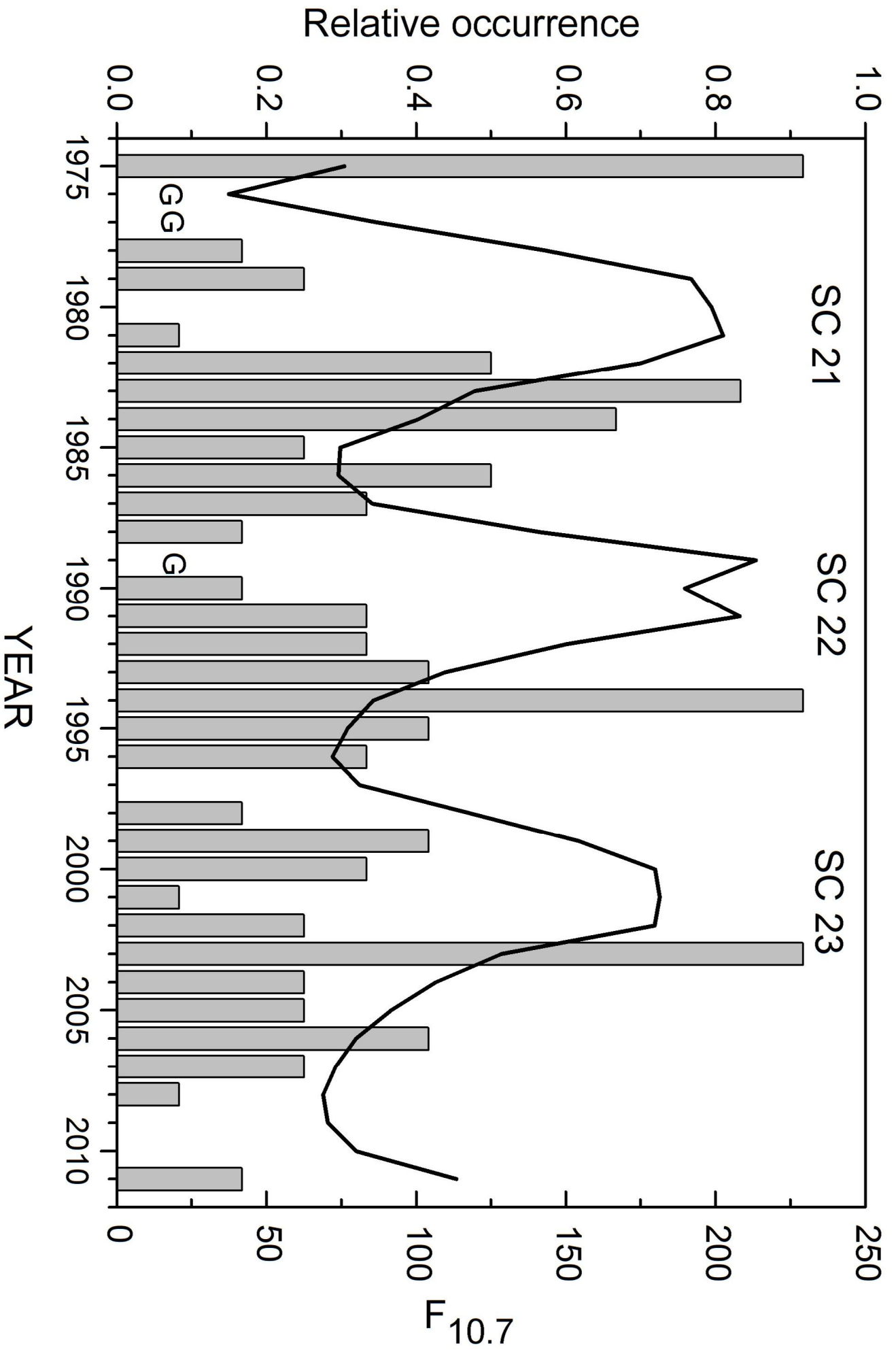
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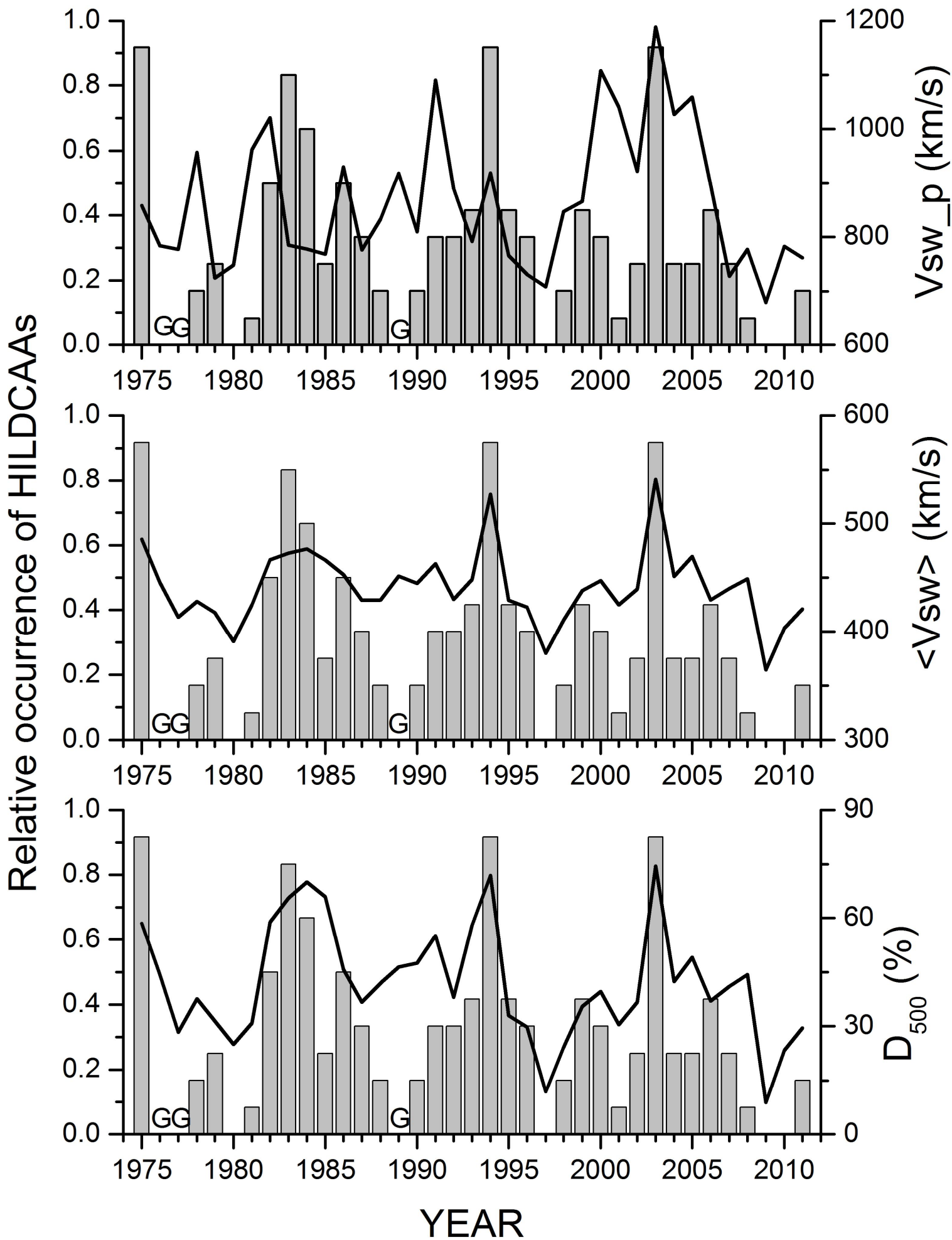


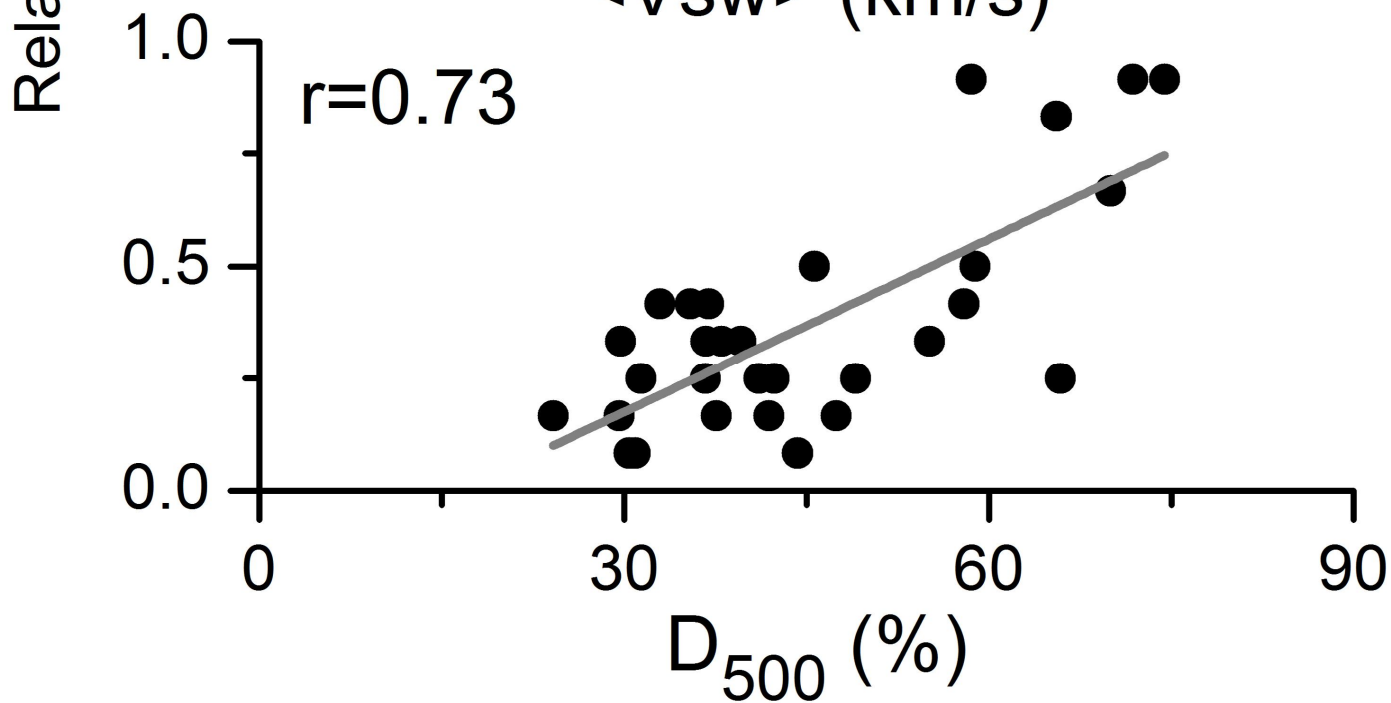
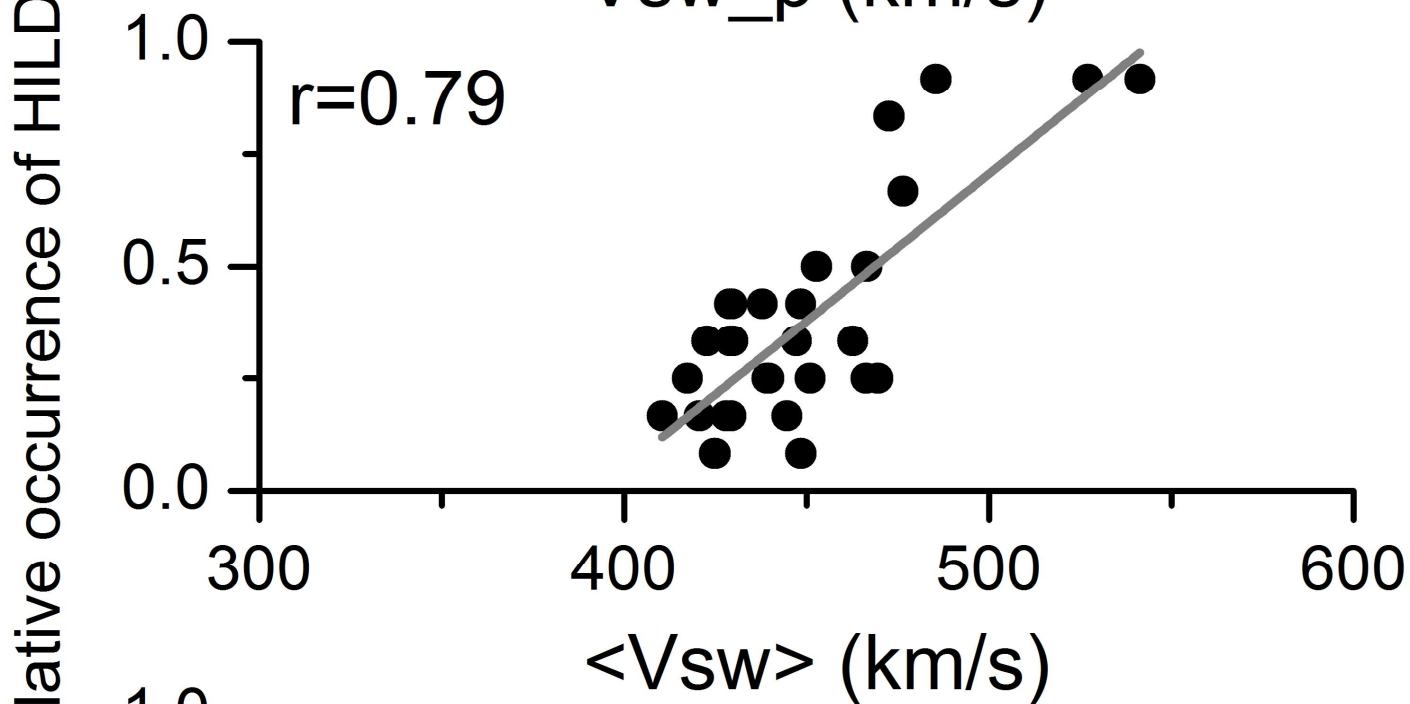
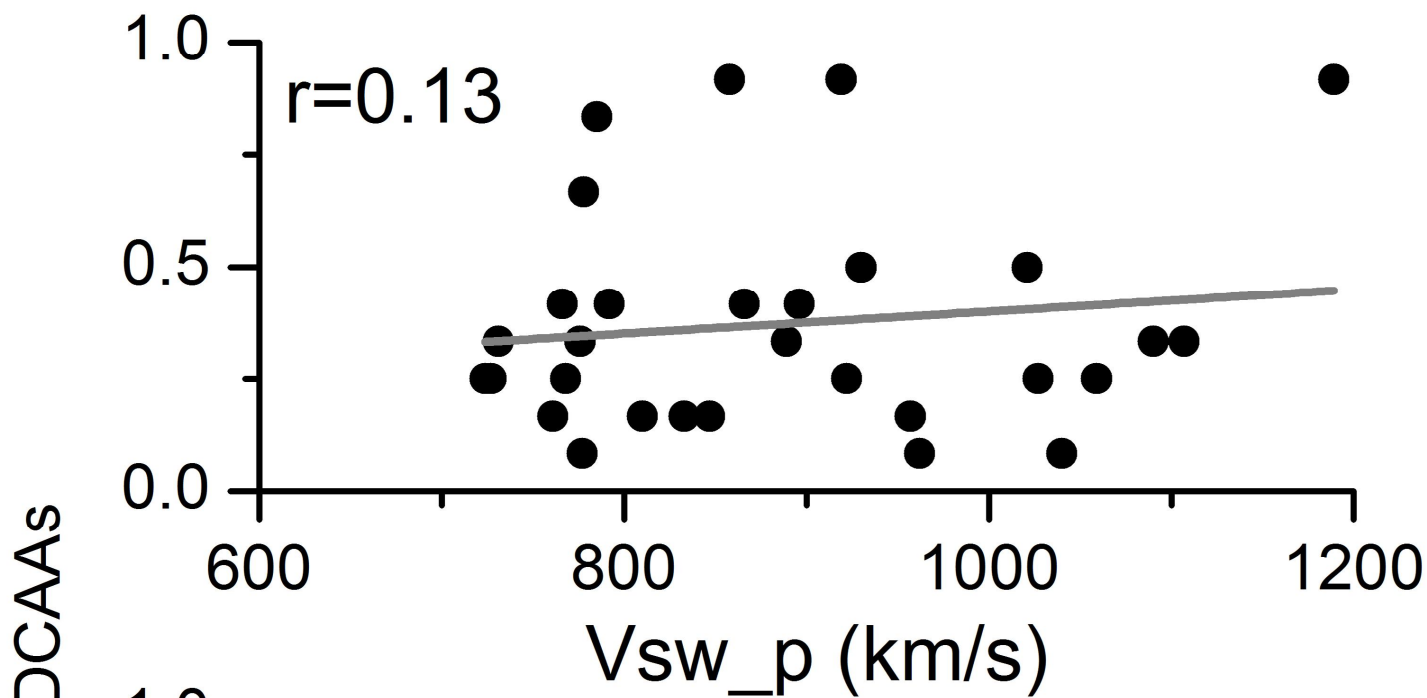
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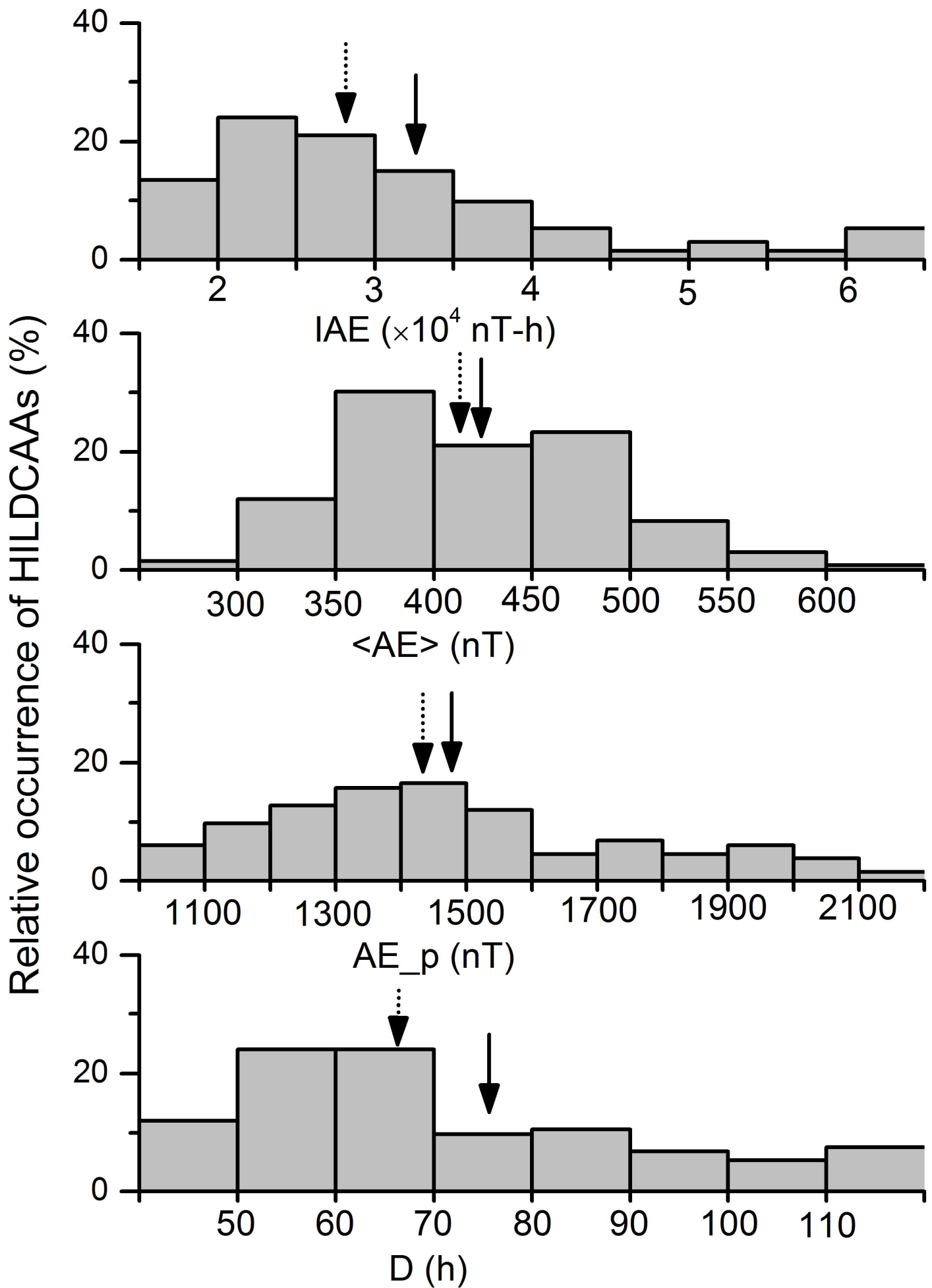


Table 1. Statistical features of 133 HILDCAA events occurring during 1975-2011.

	Average±SD	Median	Maximum	Minimum
IAE (10^4 nT-h)	3.3±2	2.8	16.3	1.4
<AE> (nT)	422±67.5	418.5	620.5	284.5
AE_p (nT)	1477.9±277.6	1425	2155	1041
D (day)	3.2±1.5	2.8	12.4	2

Table 2. Statistical features of HILDCAAs during different solar activity conditions. Numbers of events under each group are also shown.

	Average \pm SD	Median	Maximum	Minimum
Solar minimum (38)				
IAE (10^4 nT-h)	3.5 \pm 2.7	2.9	16.3	1.6
<AE> (nT)	409.8 \pm 59.7	396.1	549.1	302.4
AE_p (nT)	1550.2 \pm 290.5	1494	2155	1041
D (day)	3.5 \pm 2	2.8	12.4	2
Solar maximum (18)				
IAE (10^4 nT-h)	2.8 \pm 1.1	2.4	5.4	1.7
<AE> (nT)	428.6 \pm 73.9	418.3	579.2	327
AE_p (nT)	1351.2 \pm 224.5	1307.5	1866	1042
D (day)	2.7 \pm 0.8	2.5	5.3	2
Ascending phase (16)				
IAE (10^4 nT-h)	2.8 \pm 0.8	2.7	4.5	1.6
<AE> (nT)	422.1 \pm 60.5	419.5	533.2	302.4
AE_p (nT)	1464.6 \pm 254.2	1415.5	2155	1058
D (day)	2.7 \pm 0.7	2.6	4.4	2
Descending phase (61)				
IAE (10^4 nT-h)	3.5 \pm 2.3	2.8	16.3	1.4
<AE> (nT)	422.8 \pm 71	418.5	620.5	284.5
AE_p (nT)	1493.7 \pm 280.6	1458	2088	1041
D (day)	3.3 \pm 1.7	2.8	12.4	2

Table 3. Statistical features of HILDCAAs around three consecutive solar minima. Numbers of events under each group are also shown.

	Average \pm SD	Median	Maximum	Minimum
1985-1987 (13)				
IAE (10^4 nT-h)	2.9 \pm 0.8	2.9	4	1.6
<AE> (nT)	395.6 \pm 50.3	391.8	478.6	327.8
AE_p (nT)	1537.1 \pm 335.2	1506	2155	1041
D (day)	3.1 \pm 0.7	3	4.3	2.1
1995-1997 (9)				
IAE (10^4 nT-h)	2.9 \pm 1.1	2.6	5.5	1.8
<AE> (nT)	409 \pm 62.9	416.4	486.4	302.4
AE_p (nT)	1573.7 \pm 198	1512	2015	1352
D (day)	2.9 \pm 0.9	2.8	5	2.2
2007-2009 (4)				
IAE (10^4 nT-h)	1.9 \pm 0.4	1.8	2.4	1.6
<AE> (nT)	364.9 \pm 32.6	371.2	392.1	325
AE_p (nT)	1347.3 \pm 203.9	1418.5	1494	1058
D (day)	2.2 \pm 0.3	2.1	2.6	2