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Geoeffectiveness of different solar drivers, and long-term variations of the correlation between sunspot and geomagnetic activity

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Abstract

Two types of solar agents are mainly responsible for geomagnetic disturbances—long-lived coronal holes, regions of open solar magnetic field and sources of high speed solar wind (HSS) related to recurrent geomagnetic activity, and coronal mass ejections (CME's), regions of closed solar magnetic field related to sporadic geomagnetic activity. The coronal mass ejections can be additionally divided into magnetic clouds (MC's) and non-magnetic clouds, according to the presence or absence of magnetic field rotation. We compare the geoeffectiveness of HSS's, MC's and non-MC CME's. The average geoeffectiveness is highest for MC's and lowest for non-MC CME's. The average geoeffectiveness of MC's is strongly solar cycle dependent, but their number is relatively small, except around sunspot minimum when their geoeffectiveness is low. The geoeffectiveness of HSS's and non-MC CME's practically doesn't change throughout the cycle, however their relative abundance changes, and so does their relative contribution to the overall geomagnetic activity. The long-term decrease in the correlation between solar and geomagnetic activity is mainly due to the increasing number of HSS's on the declining phase of the sunspot cycle, which we suppose to be determined by the long-term changes in the tilt angle of the heliospheric current sheet.

Keywords: Long-term variations; Geoeffectiveness; Sunspot activity; Geomagnetic activity

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1. Introduction

Since the beginning of the twentieth century, both the geomagnetic activity as expressed by aa geomagnetic index and the solar activity measured by the sunspot numbers have increased, and their long-term variations are very similar (Lockwood et al., 1999). In the same time, studies of the variations of aa and sunspot number in the 11-year solar cycle show that their short-term correlation has been steadily decreasing (Kishcha et al., 1999), from 0.76 in the period 1868–1890, to 0.35 in the period 1960–1982, while the lag has increased from 0 to 3 years (Vieira et al., 2001). A number of studies have been devoted to the different solar drivers of geomagnetic activity. According to the classification of Feynman (1982), geomagnetic storms can be caused by two main solar sources—long lived, such as polar coronal holes, sources of high speed streams (HSS's) related to recurrent geomagnetic activity, and sporadic or short lived, such as solar flares and disappearing filaments, related to coronal mass ejections (CME's) and sporadic geomagnetic activity. Richardson et al. (2001) studied the sources of geomagnetic storms over nearly three solar cycles (1972–2000) and found that the most intense storms as defined by Kp index at both sunspot minimum and sunspot maximum are almost all generated by transient structures associated with CME's; weaker storms are preferentially associated with HSS's from coronal holes at solar minimum, and with CME's at solar maximum, while a small fraction of the weaker storms at both solar minimum and solar maximum are generated by slow solar wind. In a

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following paper Richardson et al. (2002) speculated that the long-term increase in the geomagnetic activity observed in the 20th century was due not to the increase in the radial component of the interplanetary magnetic field (IMF) as suggested by Stamper et al. (1999) but rather to the increased geoeffectiveness of the slow solar wind. Echer et al. (2004) dealt with the change in the correlation between solar and geomagnetic activity in the 11-year solar cycle, and found that the probable cause seems to be related to the aa index double peak structure. The second peak, related to HSS's, seems to have increased relative to the first one, related to sunspot (CME's) one. Kishcha et al. (1999) suggested that maybe we could even neglect the sporadic sunspot related activity when the annual geomagnetic indices are used.

These two types of solar drivers are fundamentally different in their magnetic field configuration. The coronal holes are regions of open magnetic field lines propagating outwards from the Sun into the interplanetary space, and the high-speed solar wind originating from them is characterized by high speed, low density and high temperature. The coronal mass ejections originate from regions of closed field lines extending far away from the Sun, with unusually low proton temperature or low plasma beta (ratio of plasma pressure to magnetic pressure), composition anomalies, bidirectional suprathermal electron strahls indicating looped magnetic field lines rooted at both ends on the Sun. Fast CME's drive shocks with enhanced plasma speed, density and temperature. An Earth-directed CME is observed as a halo around the Sun. A subclass of CME's is magnetic clouds (MC's), distinguished by enhanced magnetic field with smooth rotation inside the structure.

In the present paper we compare the geoeffectiveness of the two types of solar drivers—HSS's and CME's, additionally dividing the CME's into two types—MC's and non-MC CME's (which we will further denote as simply CME's). Our study covers 11 years, from 1992 to 2002—the period in which a fleet of satellites has been providing regular measurements of the Sun and the solar wind. It is almost entirely in the solar magnetic positive polarity cycle.

2. Data

We evaluate the geomagnetic disturbances by the planetary geomagnetic index Kp and the ring current index Dst, both from NASA OMNI database (http://nssdc.gsfc.nasa.gov/omniweb). We use the same database to identify the three different types of events—HSS's, CMEs and MCs. We define a HSS event as a sharp rise in the solar wind velocity by at least 100 km/s in no more than a day to no less than 500 km/s, accompanied by high plasma temperature and low plasma density. In the period 1992–2001 we have a total of 126 HSS events.

In the period 1992–2002 we have 92 MCs defined by high magnetic field magnitude, low proton temperature or low beta, and smooth magnetic field rotation. We have compiled this list from a number of sources: Fenrich and Luhmann (1998), Leamon et al. (2002), Vilmer et al. (2003), SOHO LASCO CME catalog (http://cdaw.gsfc.nasa.gov/CME_list/), WIND MFI magnetic cloud list (http://sprg.ssl.berkeley.edu/~davin/clouds/cloud_list.html). We define the beginning of a MC event by the beginning of the magnetic field rotation accompanied by a drop in plasma beta. For the CME's we use the list of Cane and Richardson (2003), from which all events identified as MC's have been removed, which leaves us with a total of 128 cases in the period 1997–2002. The beginning of a CME event is usually determined by distinct magnetic field discontinuities, which may be accompanied by abrupt changes in plasma parameters (Cane and Richardson, 2003).

3. Results

3.1. Average geoeffectiveness

To compare the average geoeffectiveness of CME's, MC's and HSS's, in Fig. 1a and b a superposed epoch analysis is presented of the daily averaged values of Kp and Dst indices, respectively, on days of events (day 0), one day before and after the events (days -1 and $+1$, respectively), etc. The period studied is 1997–2001 when we have data for all three types of events. In this period, HSS's and MC's appear to be equally geoeffective as expressed by the average value of Kp index on the day of the event. However, in the case of MC's Kp index recovers faster to its undisturbed value while in the case of HSS's the disturbances last longer. CME's lead to much smaller Kp values than MC's and HSS's, and like in the case of the MC's the geomagnetic activity related to them quickly recovers to its undisturbed level. This undisturbed level is higher than for MC's and HSS's, which is to be expected taking into account that the majority of CME's occur around sunspot maximum when the background activity is higher.

The average value of Dst index associated with MC's is highest, and is reached on the day of the event (Fig. 1b). The HSS-associated maximum negative Dst value is comparable, but is reached one day later. Also on the day following the event are the maximum disturbances as measured by the Dst index caused by CME's, and they are almost two times weaker than the ones caused by MC's and HSS. It should be reminded that according to the definition of a HSS which we have adopted, the day of the event is the day of the fast growth of the solar wind speed, while usually the speed continues growing and reaches its maximum on the following day (Fig. 1c), and it is significantly higher than the speed of the average MC's and CME's. The maximum speed of CME's is also on the day following the event, as is the minimum CME-related Dst value. The maximum magnetic field intensity for all three types of events is on the day of the event, and it is much higher for MC's than for CME's and HSS's which is to be expected taking into account that Cane and Richardson (2003) didn't require enhanced B for an event to be determined as a CME.

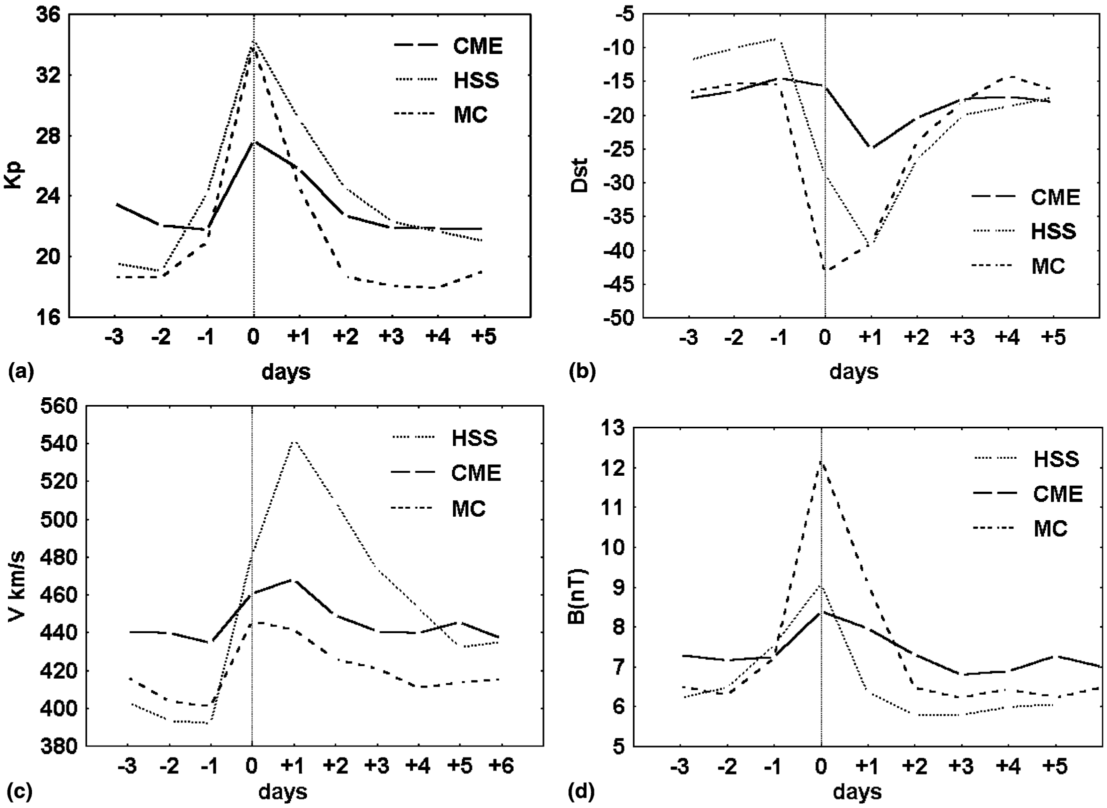

Fig. 1. Superposed epoch analysis of average daily (a) Kp index, (b) Dst index, (c) solar wind speed, and (d) IMF magnitude on days with CME's (solid line), HSS's (broken line) and MC's (dotted line) in the period 1997–2001.

The solar cycle variation of the geoeffectiveness of the different solar drivers is compared in Fig. 2a and b. The HSS-related Kp index practically doesn't change throughout the solar cycle, i.e. HSS's on average are not more geoeffective in some phase of the cycle than in any other phase. Some increase can be noted in the years around sunspot minimum and maximum but the amplitude of the variation is very small. Strong solar cycle dependence is observed for magnetic clouds. The MC-related Kp index increases 3 times from sunspot minimum to sunspot maximum. Consequently, HSS's are on the average much more geoeffective as expressed by Kp index than MC's in sunspot minimum, and MC's are much more geoeffective in sunspot maximum. CME's on the average appear to be the least geoeffective structure, at least in the period for which we have a list of CME's, which are not MC's. This means that the high geoeffectiveness of CME's as a whole reported in a number of previous studies is due to the high geoeffectiveness of MC's. The CME-associated Kp index follows the sunspot cycle and the MC-associated Kp index but its amplitude and values are much smaller than in the case of MC's.

Similar is the picture for the geoeffectiveness of these three structures as expressed by the Dst index—Fig. 2b. The HSS-related Dst index has no solar cycle variations, except for a well expressed maximum disturbance (maximum negative Dst value) in 1998 which is not seen in Kp

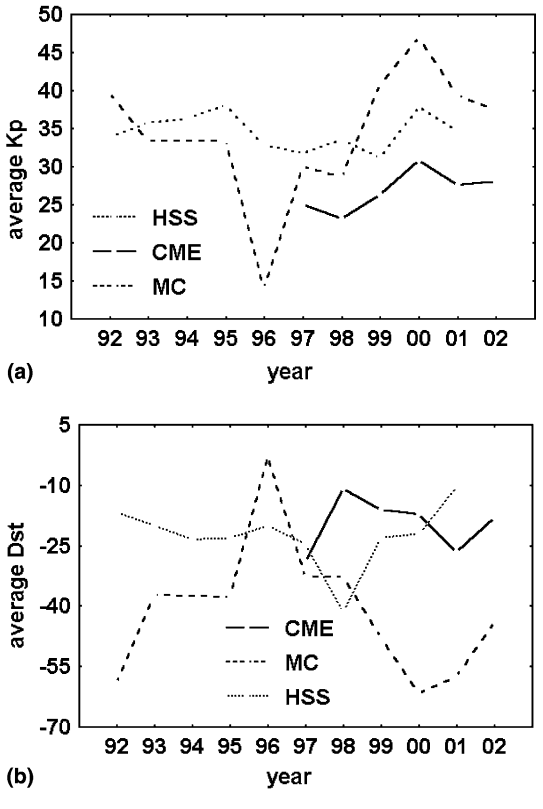

Fig. 2. Yearly averages of the daily (a) Kp index, and (b) Dst index on days with CME's (solid line), HSS's (broken line) and MC's (dotted line).

index. In 1998 HSS's are the most geoeffective solar driver, though the average ring current intensity associated with them is not very high. The geoeffectiveness of MC's again has a strong solar cycle variation, with more than 5 times increase from solar minimum to solar maximum. At solar maximum the MC's are the source of the strongest Dst disturbances, more than twice more effective than HSS's and CME's. CME's are again the least geoeffective structure, and have no expressed solar cycle dependence. We could therefore suppose that the sunspot cycle dependence of CME-related Dst index reported in previous studies (e.g. Webb, 2002) is related to the cycle variations of MC-related Dst index.

In Fig. 3a and b, the yearly averages of the velocity *V* and magnetic field magnitude *B* of HSS's, MC's and CME's are compared. For MC's, both *V* and *B* follow the sunspot cycle, with well expressed minima in sunspot minimum and maxima in sunspot maximum, which explains the solar cycle variations of their geoeffectiveness. The speed of CME's, which are not MC's, also follows the sunspot cycle. The solar cycle dependence of the speed of CME's, without dividing them into MC's and non-MC's, has been shown earlier for cycle 23 (Wu et al., 2003; Cane and Richardson, 2003), though it was not obvious for the previous cycle (Gopalswamy et al., 2003). A surprising result is the lack of whatever variations in the magnetic field magnitude of CME's, at least during the ascending phase of the solar cycle (Fig. 3b). The magnetic field magnitude of HSS's follows the sunspot cycle and in sunspot minimum its value is equal to the one of MC's, but in solar maximum it is substantially lower. The HSS speed has three peaks—one on the descending phase of the sunspot cycle (1993–94), one around sunspot maximum (2000–01) and an additional one in 1998, coinciding with the maximum in the average HSS-related Dst values.

3.2. Cumulative geoeffectiveness

The average geoeffectiveness of the different solar drivers is an important factor for the long-term variations of geomagnetic activity, but another important factor is their abundance. In the next figures we compare the "cumulative geoeffectiveness" of HSS's, MC's and CME's expressed by the daily averaged values of Kp and Dst indices summed over all days with the respective events. Thus a comparison of the cumulative geoeffectiveness of the different solar drivers provides their relative contributions to the overall geomagnetic activity.

Fig. 4a and b are superposed method analysis of the sums of Kp and Dst indices, respectively, on and around all days with HSS's, MC's and CME's. Again, for this particular figure the period used is 1997–2001 when we have data for all three types of events. The picture now is quite different from Fig. 1. Though the CME's are on the aver-

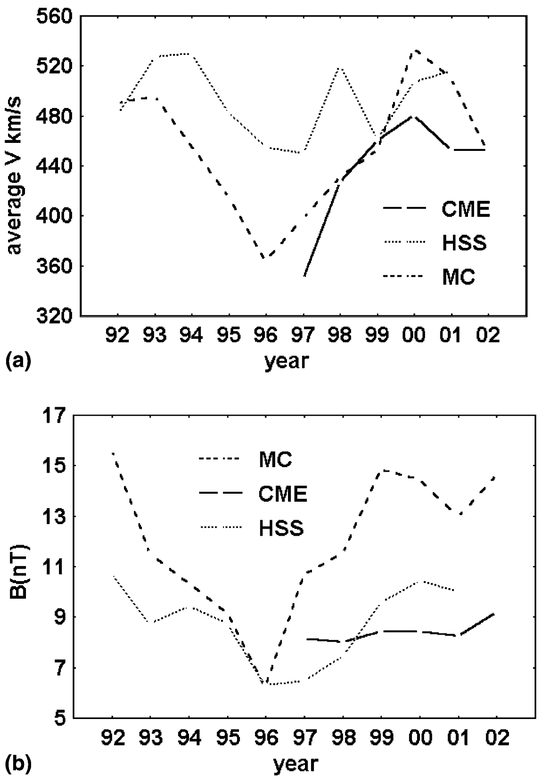

Fig. 3. Yearly averages of the daily (a) solar wind speed, and (b) IMF magnitude on days with CME's (solid line), HSS's (broken line) and MC's (dotted line).

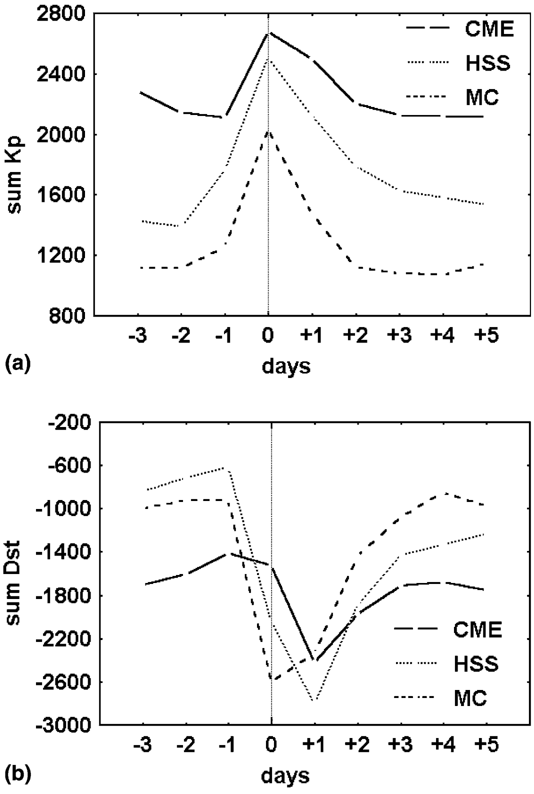

Fig. 4. Superposed epoch analysis of the sums of the daily (a) Kp index, and (b) Dst index, on days with CME's (solid line), HSS's (broken line) and MC's (dotted line) in the period 1997–2001.

age the least geoeffective events, in this period they have the biggest contribution to the overall geomagnetic activity as expressed by Kp index, while the MC's, in spite of their high average geoeffectiveness, have the smallest contribution (Fig. 4a). Expressed in Dst index (Fig. 4b), the most geoeffective are HSS's, and the least geoeffective are CME's. The maximum disturbances caused by both HSS's and CME's are again on the day following the event, while for MC's they are on the day of the event.

The different behavior of Kp and Dst index has been noted long ago. For example, Campbell (1979) has found that only about one third to one half of the low-Kp days would be quiet by Dst index standards. Fares Saba et al. (1997) demonstrated that the correlation between Dst and Kp is variable, depending on the season and with a maximum during magnetic storms. In a recent study Huttunen et al. (2002) compared the magnetospheric storms caused by different solar wind perturbations, and found that the behavior of Kp and Dst is different during storms caused by CME's, shocks and sheaths driven by CME's, or shocks without following CME's. Though the number of the storms, determined from Kp and Dst in their study, were about the same, only about a half of the storms fell in the same intensity category according to both indices. In fact, the two indices are proxies for different physical processes. During a magnetic storm the Earth's magnetosphere compresses, and the auroral zone's equatorward boundary moves to lower latitudes. The Kp index is a measure of the geomagnetic field disturbances at subauroral latitudes and a proxy for the auroral zone position. Due to the trapping of fresh plasma-sheet material in the inner magnetosphere, the ring current increases drastically in the course of the storm. The ring current induces a magnetic field with an opposite sigh to the Earth's ambient field, adds to it and depresses it. The Dst index is a measure of the magnetic field depression at low latitude stations and a proxy for the ring current intensity. The delay in the reaction of the Dst index relative to Kp also noted by Huttunen et al. (2002) may be explained by the delayed maximum in solar wind speed in the case of CME's and HSS's, but it also demonstrates that the ring current needs more time to build up than the magnetosphere to compress (Gonzalez et al., 1994). Dst has no delay in the case of MC's, its maximum negative value is on the day of the event. This may be related to the criterion which we have applied for the beginning of a MC—the beginning of the magnetic field rotation which is usually well after the eventual shock. Moreover, the majority of MC's in the period studied (corresponding to positive solar magnetic polarity), are S-N type (Bothmer, 2003), so the beginning of the magnetic field rotation coincides with the maximum negative Bz value.

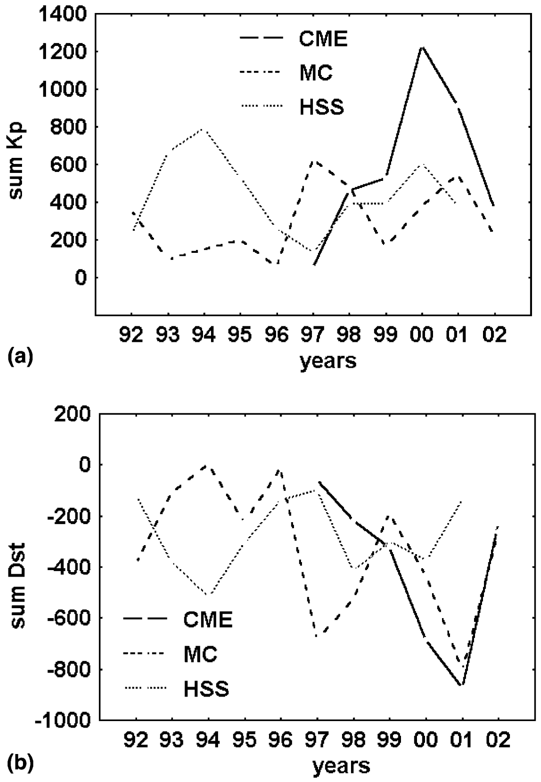

Fig. 5. Yearly sums of the daily (a) Kp index, and (b) Dst index on days with CME's (solid line), HSS's (broken line) and MC's (dotted line).

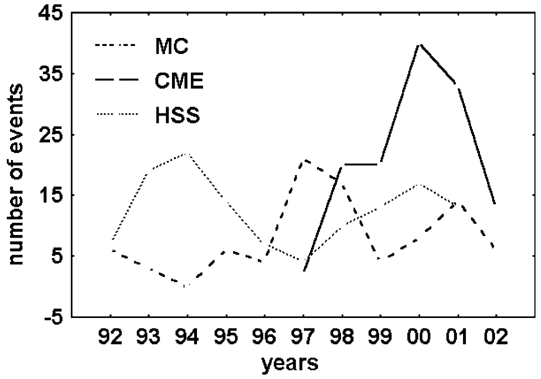

Fig. 6. Yearly number of the observed CME's (solid line), HSS's (broken line) and MC's (dotted line).

In Fig. 5 the solar cycle variations of the cumulative geoeffectiveness of the three types of events is compared, and in Fig. 6—the yearly number of the events. Due to their large number, in solar maximum the CME's have the highest impact to the overall geomagnetic activity as expressed by Kp index (Fig. 5a), while at the descending phase of the sunspot cycle the agent which contributes most to the Kp are the HSS's. 1994–95 is the period with not only the biggest number of HSS's but also of HSS's with highest speed. The contribution of HSS's to the total Kp activity is substantial also in sunspot maximum, and has a minimum around sunspot minimum and in 1997. Though the MC's are the most geoeffective solar driver, their number is relatively small and consequently their cumulative geoeffectiveness is not high. A maximum in the sum of MC-associated Kp index is seen in 1997, which was a year with unusually high number of MC's (Wu et al., 2003). Solar minimum is the period with the highest portion of CME's which are MC's (Richardson and Cane, 2004), however their absolute number is not high and the overall geomagnetic activity as expressed by Kp index related to MC's is low around sunspot minimum.

For geomagnetic activity expressed by Dst index, the situation is somewhat different (Fig. 5b). The maximum in Dst is not in the year of the sunspot maximum, 2000, but in the following 2001, and the contributions of CME's and MC's in this year are almost equal. For both CME's and MC's the geoeffectiveness decreases towards sunspot minimum, again with the exception of year 1997 when the high number of MC's leads to a peak negative Dst value. The HSS-associated cumulative Dst has three maxima coinciding with the maxima in their speed: 1994, 1998 and 2000, the strongest one being in 1994 which is the maximum in both HSS's speed and number (Fig. 6).

4. Summary and discussion

We have compared the average and cumulative geoeffectiveness in the last solar cycle of two types of solar sources of geomagnetic activity—high speed solar streams originating from coronal holes (regions of open solar magnetic field) and coronal mass ejections (originating from regions of closed solar magnetic field) with the goal to understand the reason for the long-term changes of the correlation between solar and geomagnetic activity. We find that on the average the most geoeffective solar driver are not CME's in general but MC's—a subclass of CME's with a magnetic field rotation inside the structure. Non-MC CME's are less geoeffective than HSS's. The average geoeffectiveness of MC's is strongly solar cycle dependent, but their number is relatively low, except around sunspot minimum when their geoeffectiveness is small. The geoeffectiveness of HSS's and non-MC CME's practically doesn't change throughout the cycle, however their relative abundance changes, and so does their cumulative geoeffectiveness. Therefore the relative contribution of the different types of solar drivers to geomagnetic activity mainly depends on their number—compare Fig. 6 to Fig. 5a. So the geomagnetic activity at sunspot maximum is mainly caused by the large number of non-MC CME's whose average geoeffectiveness is not high, and the small number of strong MC's, both originating from closed solar magnetic field regions, and by the large number of HSS's originating from open solar magnetic field regions. Around sunspot minimum when almost all CME's are MC's, the contributions by MC's and HSS's are comparable, while on the declining phase of the sunspot cycle the geomagnetic activity is very predominantly due to the large number of HSS's. We could therefore suppose that the power of this maximum in geomagnetic activity on the declining phase of sunspot activity depends on the number of HSS's, and the question about the geomagnetic activity maximum on the declining phase of the sunspot cycle is related to the question about the HSS's number in this period.

The sources of HSS's around solar maximum are the small low latitude coronal holes, while on the declining phase of the sunspot cycle these are mainly the big polar coronal holes (Wang and Sheeley, 2002). Recurrent geomagnetic activity on the declining phase of the sunspot cycle driven by recurrent streams of HSS's can be observed at times when the Sun's polar coronal holes extend towards the solar equator, forming a thin heliospheric current sheet with large speed gradients across it (e.g. Burlaga and Lepping, 1977). If the current sheet becomes sufficiently tilted, the Earth encounters two high-speed streams per solar rotation (Zhao and Hundhausen, 1981). The presence of two HSS's per solar rotation associated with coronal holes leads to a larger number of HSS's and exceptionally high geomagnetic activity (Tsurutani et al., 1995). Mursula and Zieger (1996) studied the half solar rotation (~13.5 days) periodicity in solar wind, IMF and geomagnetic activity, occurring when the interplanetary magnetic field has a two-sector structure and the solar dipole (heliosheet) is sizably tilted, so there are two HSS's per rotation. They found that the power of this periodicity was lower in cycles 9–13 than in the more recent cycles, and even more importantly, during these low sunspot cycles, the ~13.5 day periodicity related to two HSS's per solar rotation tended to occur before or around sunspot maximum, while during the later high sunspot cycles, it moved to the declining phase of the sunspot cycle (see their Fig. 1). We could therefore conclude that the long-term changes of the correlation between sunspot and geomagnetic activity are related to the changing tilt angle of the heliospheric current sheet.

Mursula and Zieger (1998) explain the long-term variations of the power of the 13.5-day periodicity by the long-term changes in sunspot activity. They speculate that the solar dipole moment was weaker at the end of the ninetieth and beginning of the twentieth century than during the more recent cycles, and that coronal evolution during these slowly increasing, low sunspot number cycles was very stable, with a flat heliosheet and open coronal holes until close to sunspot maximum. Furthermore, they suggest that new sunspot groups and solar dipole tilt are generally related, being probably due to common magnetic processes. This could be a possible explanation of the long-term decrease in the correlation between sunspot and geomagnetic activity with the century-scale increase of solar activity.

References

Bothmer, V., 2003. Sources of magnetic helicity over the solar cycle. In: Wilson, A. (Ed.), Solar Variability as an Input to the Earth's Environment. ESA SP-535, pp. 419–428.

Burlaga, L.F., Lepping, R.P., 1977. The causes of recurrent geomagnetic storms. Planet. Space Sci. 25, 1151–1160.

Campbell, W.H., 1979. Occurrence of AE and Dst geomagnetic index levels and the selection of the quietest days in a year. J. Geophys. Res. 84, 875–881.

Cane, H.V., Richardson, I.G., 2003. Interplanetary coronal mass ejections in the near-Earth solar wind during 1996–2002. J. Geophys. Res. 108 (A4), 1156. doi:10.1029/2002JA009817.

Echer, E., Gonzalez, W.D., Gonzalez, A.L.C., Prestes, A., Vieira, L.E.A., dal Lago, A., Guarnieri, F.L., Schuch, N.J., 2004. Long-term correlation between solar and geomagnetic activity. J. Atm. Solar-Terr. Phys. 66 (12), 1019–1025.

Fares Saba, M.M., Gonzalez, W.D., Clua de Gonzalez, A.D., 1997. Relationships between AE, ap and Dst indices near solar minimum (1974) and solar maximum (1979). Ann. Geophys. 15, 1265–1270.

Fenrich, F.R., Luhmann, J.G., 1998. Geomagnetic response to magnetic clouds of different polarity. Geophys. Res. Lett. 25 (15), 2,999–3,002.

Feynman, J., 1982. Geomagnetic and solar wind cycles, 1900–1975. J. Geophys. Res. 87, 6153–6162.

Gonzalez, W.D., Joselyn, J.A., Kamide, Y., Kroehl, H.W., Rostoker, G., Tsurutani, B.T., Vasyliunas, V.M., 1994. What is a geomagnetic storm? J. Geophys. Res. 99, 5771–5792.

Gopalswamy, N., Lara, A., Yashiro, S., Nunes, S., Howard, R.A., 2003. Coronal mass ejection activity during solar cycle 23, In: Wilson, A. (Ed.), Solar Variability as an Input to the Earth's Environment. ESA SP-535, pp. 403–414.

Huttunen, K.E.J., Koskinen, H.E.J., Schwenn, R., 2002. Variability of magnetospheric storms driven by different solar wind perturbations. J. Geophys. Res. 107 (A7). doi:10.1029/2001JA900171.

Kishcha, P.V., Dmitrieva, I.V., Obridko, V.N., 1999. Long-term variations of the solar-geomagnetic correlation, total solar irradiance, and northern hemispheric temperature (1868–1997). J. Atm. Solar-Terr. Phys. 61 (11), 799–808.

Leamon, R.J., Canfield, R.C., Pevtsov, A.A., 2002. Properties of magnetic clouds and geomagnetic storms associated with eruption of coronal sigmoids. J. Geophys. Res. 107 (A9), 1234–1243.

Lockwood, M., Stamper, R., Wild, M.N., 1999. A doubling of the sun's coronal magnetic field during the last 100 years. Nature 399 (3), 437–439.

Mursula, K., Zieger, B., 1996. The 13.5-day periodicity in the Sun, solar wind, and geomagnetic activity: the last three solar cycles. J. Geophys. Res. 101 (A12), 27077–27090.

Mursula, K., Zieger, B., 1998. Solar excursion phases during the last 14 solar cycles. Geophys. Res. Lett. 25 (11), 1851–1854.

Richardson, I.G., Cane, H.V., 2004. The fraction of interplanetary coronal mass ejections that are magnetic clouds: evidence for a solar cycle variation. Geophys. Res. Lett. 31, L8804. doi:10.1029/2004GL020958.

Richardson, I.G., Cliver, E.W., Cane, H.V., 2001. Sources of geomagnetic storms for solar minimum and maximum conditions during 1972–2000. Geophys. Res. Lett. 28, 2569–2572.

Richardson, I.G., Cliver, E.W., Cane, H.V., 2002. Long-term trends in interplanetary magnetic field strength and solar wind structure during the twentieth century. J. Geophys. Res. 107 (A10), 1304. doi:10.1029/2002JA000507.

Stamper, R., Lockwood, M., Wild, M.N., Clark, T.D.G., 1999. Solar causes of the long-term increase of the geomagnetic activity. J. Geophys. Res. 104 (A12), 28235–28342.

Tsurutani, B., Gonzalez, W., Gonzalez, A.L.C., Tang, F., Arballo, J.K., Okada, M., 1995. Interplanetary origin of geomagnetic activity in the declining phase of the solar cycle. J. Geophys. Res. 100 (A11), 21717–21734.

Vieira, L.E., Rigozo, N.R., Echer, E., Nordemann, D.J., 2001. Geomagnetic-solar activity correlation evolution. AGU Spring Meeting 2001, abstract #SH52A-05.

Vilmer, N., Pick, M., Schwenn, R., Ballatore, P., Villain, J.P., 2003. On the solar origin of interplanetary disturbances observed in the vicinity of the Earth. Ann. Geophys. 21 (4), 847–862.

Wang, Y.-M., Sheeley, N.R., 2002. Sunspot activity and the long-term variation of the Sun's open magnetic flux. J. Geophys. Res. 107 (A10), SSH10-1.

Webb, D., 2002. CMEs and the solar cycle variation in their geoeffectiveness, In: Wilson, A. (Ed.), Proceedings of the SOHO 11 Symposium on From Solar Min to Max: Half a Solar Cycle with SOHO. ESA SP-508, pp. 409–419.

Wu, Ch.-Ch., Lepping, R.P., Gopalswamy, N., 2003. Variations of magnetic clouds and CMEs with solar activity cycle. In: Wilson, A. (Ed.), Solar Variability as an input to the Earth's Environment. ESA SP-535, pp. 429–432.

Zhao, X.-P., Hundhausen, A.J., 1981. Organization of solar wind plasma properties in a tilted, heliomagnetic coordinate system. J. Geophys. Res. 86, 5423–5430.