Geophysical effects of solar activity: long-term variations in occurrences of magnetic storms with sudden and gradual commencements

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Abstract. Magnetic storms with sudden and gradual commencements are related to different agents of solar activity and form two independent populations. Coronal mass ejections which are more frequently related to active regions on the Sun (local magnetic fields with closed configuration) give rise, as a rule, to magnetic storms with sudden commencements. High-speed streams of solar wind related to solar coronal holes (regions of magnetic fields with open configuration) give rise to magnetic storms with gradual commencements. In this work we studied annual occurrences of magnetic storms with sudden and gradual commencements on the base of the data from IZMIRAN and Slutsk (Pavlovsk) magnetic observatories for the period 1878-2015, the correlation and spectral analysis being used. It was found that the occurrences of large and moderate magnetic storms with gradual commencements are characterized by long-term variations at the multidecadal and secular time scales. Wavelet spectra of occurrences of these storms reveal a dominant periodicity of ~36 years (close to the Brückner cycle) and less pronounced ~60-year and ~90-year periodicities on the entire time interval under study. It was found that ~11-year variations in occurrences of storms with gradual commencements were the most statistically significant in ~1900-1920 and ~1980-2000, but they were not observed in ~1940-1960. The occurrence of magnetic storms with sudden commencements is characterized by a dominant ~11-year periodicity almost on the entire interval of observations, whereas long-term variations are less pronounced. The obtained results provide evidence for a different time evolution of global and local solar magnetic fields.

1. Introduction

It is known that geomagnetic activity is caused by disturbed solar wind streams which interact with the Earth’s magnetosphere. There are two main solar sources of geomagnetic disturbances: coronal mass ejections (CMEs) and high-speed solar wind streams from coronal holes (e.g. [1-2]). These sources are associated with different kinds of solar magnetic fields. Coronal mass ejections are large plasma clouds ejected from the Sun, with embedded magnetic fields. They are more frequently related to solar active regions characterized by strong local magnetic fields with closed configuration. Their contribution to geomagnetic activity is highest at maxima of the 11-year solar cycle. High-speed solar wind streams are related to coronal holes which are large areas of magnetic fields with open configuration and depend on large-scale and global solar magnetic fields. The contribution of high-speed streams from coronal holes is most significant in a declining phase of the solar cycle.
Magnetic storm is a strong perturbation of the Earth’s magnetic field which is due to an enhancement of the ring current existing in the Earth’s radiation belts. For the development of a magnetic storm a sustained period of a southward (i.e. opposite to the Earth’s magnetic field direction) component of solar wind magnetic field is needed. Magnetic storms can be divided into two classes: storms with sudden and gradual commencements. When a CME-associated interplanetary shockwave compresses the magnetosphere, a sudden increase of the Earth’s magnetic field occurs. If a magnetic storm starts after this increase, it is referred as a magnetic storm with sudden commencement (SC). Magnetic storms with gradual commencements (GC) are not preceded by such increases and develop gradually. Usually they arise due to high-speed solar wind streams from coronal holes. The interaction of high-speed and slow solar wind streams result in the formation of co-rotating interaction regions (CIRs) with compressed magnetic field. As it was shown [3], magnetic storms with sudden and gradual commencements, being related to different solar agents, form two independent populations. Thus, time variations in frequencies of occurrence of magnetic storms with sudden and gradual commencements may characterize the evolution of solar agents associated with local and global solar magnetic fields. So, the aim of this work is to study variations in frequency of occurrence of these two types of magnetic storms at the decadal and multidecadal time scales.

2. Experimental data and their analysis

As experimental base of this study we used the data of the mid-latitude magnetic observatories IZMIRAN (55°45′N, 37°37′E; geomagnetic latitude Φ~51°) for 1934-2015 and Pavlovsk/Slutsk (59°57′N, 30°42′E; Φ~58°) for 1878-1940 presented in [4-5]. These data contain the lists of magnetic storms with sudden and gradual commencements of different intensities (small, moderate, large and very large). The storm intensity is defined according to the amplitude deviation of the Earth’s magnetic field components H (horizontal), Z (vertical) and D (magnetic declination) [5]. The horizontal component H decreases by 80-125 nT during small storms, 126-200 nT during moderate storms, 201-270 nT during large storms and ≥270 nT during very large storms. On the base of the data [4-5] annual frequencies of occurrence (number of events during a year) of magnetic storms with sudden (SC) and gradual (GC) commencements were calculated for different intensity ranges.

In figure 1 annual frequencies of occurrence of SC and GC magnetic storms are compared to sunspot number variations SSN [6], with the polynomial trends of the 2nd order in these values being shown. As large and very large storms are rather rare events, we combined them into one group. Small magnetic storms are not presented in figure 1, as no data were available until 1950. One can see an increase of sunspot numbers from the end of the 19th century, with the maximum being reached in the middle of the 20th century, and a subsequent decrease. The annual occurrences of SC magnetic storms, both large and moderate, and large GC storms reveal the polynomial trends similar to that in sunspot numbers. As to moderate GC storms, the polynomial trend in their occurrence somewhat differs from the SSN trend. The frequency of occurrence of these storms increased slower until the mid-20th century and then decreased faster than sunspot numbers.

The data in figure 1 show that SC storms, both large and moderate, are closely related to sunspot number variations, whereas GC storm occurrences do not reveal such a close relationship. The correlation coefficients between the frequencies of occurrence of magnetic storms under study and sunspot numbers for the period 1878-2015 are given in Table 1. The statistical significance of the correlation coefficients was estimated using the random phase test [7].

|                      | SC storms | GC storms |
|----------------------|-----------|-----------|
| Large + very large   | 0.73 (98%)| 0.36 (95%)|
| Moderate             | 0.72 (97%)| 0.24 (−)  |
| Large + very large + moderate | 0.82 (98%)| 0.32 (−)  |
Figure 1. Annual frequencies of occurrence (number of events during a year) of magnetic storms with sudden (a, b) and gradual (c, d) commencements (solid lines). Sunspot numbers are shown with blue bar chart. The polynomial trends are shown with dashed lines for magnetic storm occurrences and with dotted lines for sunspot numbers.

It is seen that the occurrences of magnetic storms with sudden commencements really correlate well with sunspot numbers, which is due to a close link of these events with CMEs. The correlations with SSN are noticeably less for the occurrences of magnetic storms with gradual commencements. Whereas large GC storms reveal not very high, but statistically significant link with sunspot numbers, moderate storms seem not to depend on them. The dependence of magnetic storm occurrences on sunspot numbers is shown in figure 2. One can note that a rather large number of GC storms occurred at minima of the 11-year solar cycle when SSN is small (less than 20-30).

Figure 2. Annual frequency of occurrence of magnetic storms with sudden (a) and gradual (b) commencements of all intensities (moderate, large and very large) versus sunspot numbers.
Let us consider spectral characteristics of the magnetic storm occurrences. In figures 3 and 4 we present the local and global wavelet spectra (basis Morlet) of annual frequencies of occurrence of large and moderate magnetic storms with sudden and gradual commencements. The spectra were calculated after the removal of the polynomial trends of the 2nd order and normalized by variance.

**Figure 3.** Local (a, c) and global (b, d) wavelet spectra (basis Morlet) of annual frequencies of occurrence of large and moderate magnetic storms with sudden commencements after the removal of the polynomial trends. All the spectra were normalized by variance.

**Figure 4.** The same as in figure 3, but for large and moderate magnetic storms with gradual commencements.
The data presented in figures 3 and 4 show that the spectra of frequencies of occurrence differ significantly for magnetic storms with sudden and gradual commencements. The studied occurrences of SC magnetic storms, both of large and moderate intensities, are characterized by dominating 11-year periodicities, with long-term variations being substantially weaker. On the contrary, the spectra of GC storm occurrences demonstrate a predominance of long-term variability, the variations with the period \( \sim 36 \) years being the most significant. This periodicity corresponds to the well-known Brückner cycle observed in a number of meteorological and geophysical characteristics (e.g. [8]). The \( \sim 11 \)-year periodicity in the occurrence of GC magnetic storms is on the average weaker than the \( \sim 36 \)-year one. Let us note that periodicities of \( \sim 30-40 \) years, as well as less pronounced \( \sim 60 \)-year ones are observed on the entire time interval under study for magnetic storms with gradual commencements, both large and moderate. The occurrence of large GC magnetic storms reveals in addition a persistent \( \sim 90 \)-year periodicity which is close to the Gleissberg secular cycle.

Concerning the \( \sim 11 \)-year periodicities in the spectra of annual occurrences of magnetic storms both with sudden and gradual commencements, we can note that their intensities reveal a striking temporal variability. The \( \sim 11 \)-year periodicities dominating in the spectra of SC storms were most pronounced from \( \sim 1920 \) to the early 2000s, and especially in \( \sim 1940-1960 \), but they were insignificant from the end of 19\(^{th} \) century to the early 1900s, i.e. in the period of low solar cycles (a minimum of the Gleissberg cycle). At present they seem to start weakening again. The above data allows suggesting that the \( \sim 11 \)-year variations in occurrences of magnetic storms with sudden commencements enhance with a secular rise of solar activity and weaken with its secular lowering. On the contrary, the \( \sim 11 \)-year variations in occurrences of magnetic storms with gradual commencements, both large and moderate, seem to be rather weak in the period \( \sim 1940-1960 \) when a secular maximum of solar activity took place. These periodicities were most enhanced in \( \sim 1900-1920 \) (a minimum of the secular cycle) and \( \sim 1980-2000 \) (a declining phase of the secular cycle).

The detected temporal variability in occurrences of magnetic storms with sudden and gradual commencements provides evidence for a quite different character of the evolution of their solar sources, local and large-scale magnetic fields contributing, respectively, to the formation of CMEs and high-speed solar wind streams. The above data confirm that the evolution of local magnetic fields is characterized by a strong \( \sim 11 \)-year variability. This variability seems to be enhanced at secular solar maximum. However, long-term variations of local magnetic fields on the Sun are likely to be substantially less pronounced. As to large-scale and global solar magnetic fields, their evolution apparently undergoes significant changes at the multidecadal and century time scales. The \( \sim 11 \)-year periodicity in their development seems to be enhanced at secular minimum and during a declining phase of the secular solar cycle, whereas at secular maximum it apparently weakens. The obtained results show that magnetic storms of different types may provide important information about variations of magnetic fields on the Sun.

3. Conclusions

The results of this study showed that annual frequencies of occurrence of magnetic storms with sudden and gradual commencements demonstrate different temporal variations, as well as different relationships with sunspot numbers. Both large and moderate magnetic storms with sudden commencements, usually related to coronal mass ejections, reveal a close association with the 11-year solar cycle (high positive correlation with sunspot numbers). The spectra of their occurrences are characterized by dominating \( \sim 11 \)-year periodicities enhanced at secular solar maximum, with long-term variations being weak. Magnetic storms with gradual commencements, related, as a rule, to high-speed streams from coronal holes, do not reveal significant correlations with sunspot numbers. The spectra of their occurrences demonstrate a predominance of persistent long-term variations (periods from \( \sim 30 \) to \( \sim 100 \) years), with a \( \sim 36 \)-year periodicity close to the Brückner cycle being the most significant. The \( \sim 11 \)-year variations in occurrences of both large and moderate magnetic storms with gradual commencements seem to depend on the phase of a secular solar cycle. They were found to be
enhanced at minimum and in a declining phase of the secular cycle. The obtained results allow suggesting a different character of temporal evolution of magnetic fields on the Sun which are responsible for solar agents contributing to the development of magnetic storms with sudden and gradual commencements.

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