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Long-Term Trends and Seasonal Variations in Geomagnetic Storms from Data of St. Petersburg Observatories (1878–1954)

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Abstract—The annual number of magnetic storms *N* recorded at St. Petersburg observatories (Pavlovsk/Slutsk and Voyeykovo) in 1878–1954 is studied. The analysis shows that *N* has increased since ~1900 for different storm types (storms with sudden commencement Ssc and storms with gradual Sg commencement; moderate, strong and very strong); however, the number of Ssc storms increased more rapidly than the number of Sg storms. The percentage of Ssc storms doubled for the first half of the 20th century, while the number of Sg storms decreased by 1.5 times. The Ssc storms are driven by coronal mass ejections from closed magnetic structures on the Sun, and Sg storms are driven by corotating fluxes from open magnetic structures and coronal holes. These results are apparently evidence of an increase in the activity of both types of solar magnetic structures in the first half of the 20th century and a more rapid increase in the activity of fields with closed lines of forces. A semiannual variation with maxima in the periods of vernal and autumnal equinoxes is clearly pronounced for Sg and moderate storms. The tendency to have two equinoctial maxima is pronounced in the total number of storms *N* for both even and odd cycles; however, maxima that differ from the arithmetic mean by more than a standard deviation are observed only in September in even cycles and in March in odd cycles.

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1. INTRODUCTION

The study of long-term trends and seasonal variations in the geomagnetic activity is important for the physics of solar–terrestrial relationships and the forecast of the cosmic weather and cosmic climate. Both of these questions have been the subject of much discussion for the last two decades. Various authors since the 1970s have found an increase in geomagnetic activity expressed by the aa index (Mayaud, 1973; Russel, 1975; Feynmnan and Crooker, 1979). It was found (Lockwood et al., 1999) that the aa index of geomagnetic activity increased by 2.3 times for 1869–2000, from which the authors concluded that the heliospheric magnetic field magnitude doubled in the 20th century, as well as the open magnetic fields of the Sun, which are sources of heliospheric fields. However, these results were criticized. Svalgaard et al. (2003) pointed that the aa index does not show this growth when calibrating data for different periods of the 20th century. In the study of other indices, no increase was observed either (Ponyavin, 2001; Kobylyansky et al., 2005). No significant changes in the magnitude of the heliospheric magnetic field have been found since 1951 (Richardson et al, 2002). Arge et al. (2002) dispute the results of Lockwood et al. (1999), referring to the results of direct measurements of the intensity of large-scale solar magnetic fields, which have been carried out since 1967; these results are evidenc of an absence of their increase. On the other hand, Makarov et al. (2002) stated that the increase in the magnetic flux from the Sun in the 20th century can be explained by an increase in the region of polar zones occupied by the unipolar field rather than by an increase in the field intensity.

The fact that the long-period averaged geomagnetic activity is higher in the equinox periods than in the solstice periods has been known for more than a hundred years. Several explanations have been proposed for this effect (Rosenberg and Coleman, 1969; Russell and McPherron, 1973; Russel, 1974; Cliver et al., 1996). However, there is no ambiguous explanation of this semiannual variation. Moreover, the data for solar cycles 23 and 24 were examined in a recent work (Mursula et al., 2011), and the authors have suggested that the semiannual variation is an artifact obtained from summation of two annual waves with a spring maximum for even and autumn maximum for odd cycles. This 22-year variation is attributed by the authors to the asymmetry of the magnetic flux from the northern and southern hemispheres of the Sun.

Long-term evolution and seasonal variations in the geomagnetic activity are mainly studied with the use of various activity indices, especially the aa index, which has the longest series of observations, from 1868. Our analysis is based on geomagnetic storms recorded at St. Petersburg observatories (Pavlovsk/Slutsk and Voyeykovo) in 1878–1954. Geomagnetic storms are planetary disturbances of the geomagnetic field caused by the interaction between the Earth's magnetosphere and the solar matter. They are divided into two classes: Ssc storms with a sudden commencement and Sg storms with a gradual commencement. The sudden commencement of geomagnetic activity (Ssc) is caused by a sudden increase in the dynamic pressure of the solar wind near the Earth's orbit. At this time, an interplanetary shock wave is usually observed in the solar wind, the disturbed state of which is often associated with a coronal mass ejection (CME) (Lindsay et al., 1994). A magnetic disturbance associated with Ssc propagates to the Earth's surface and is recorded in magnetograms as a sharp jump. The detection of an Ssc event depends on the criteria accepted (the jump amplitude, duration, the number of stations where it is observed) and, especially, on the subsequent disturbance of the magnetic field. At the General Assembly of the IAGA in 1969, it was accepted that Ssc is a sudden pulse followed by a magnetic storm or a 1-h increase in the activity. Somewhat later, Mayaud (1973) presented the list of Ssc storms for 100 years with qualifying criteria that were very different from the commonly accepted ones. He proposed to consider as Ssc those pulses that follow by a "change in the rhythm" of the geomagnetic activity, regardless of the amplitude of this activity. This definition has been used so far, although it is rather subjective (Curto et al., 2007). Moreover, according to Curto et al. (2007), authors who use Ssc lists composed in this way to select magnetic storms note that they often detect only weak disturbances instead of storms. Since 1976, Ssc lists have been regularly published in the IAGA Bulletin. Early catalogs (Moos, 1910; McNish, 1934; Kalinin and Benkov, 1941; Newton, 1948) were compiled using the authors' own criteria and, hence, the Ssc lists differed from each other and from later lists. Despite this, morphological features found with those catalogs were generally in agreement (Curto et al., 2007).

It is known that geomagnetic disturbances are caused mainly by two solar sources (Simon and Legrand, 1989; Gonzalez et al., 1994; Tsurutani et al., 2006; Love, 2011): (1) transient solar coronal mass ejections and (2) corotating high-speed fluxes from coronal holes. It was suggested that Ssc storms are driven by CMEs and Sg storms are driven by corotating fluxes (Taylor et al, 1994). Borovsky and Danton showed that one of the features of CME-driven storms is a sudden commencement, which is rare in storms driven by high-speed corotating fluxes. Additional evidence in support of that idea was obtained by Obridko et al. (2013). CMEs and corotating fluxes lead to the development of a magnetic storm in the cases where they are accompanied by a significant southern component of the interplanetary magnetic field Bz.

The purpose of our work is to study (1) long-term trends in the frequency of occurrence of magnetic storms of various types in 1878–1954; (2) seasonal variation in storms taking into account the evenness of solar cycles on a long time basis, and (3) the relationship between the identified features and sources on the Sun. The main emphasis is placed on the analysis of storms with sudden and gradual commencement.

2. DATA

We used data from the electronic catalog (Soldatov et al., 2016; http://www.wdcb.ru/stp/data/storms/magnetic_storms/) of magnetic storms recorded at the St. Petersburg observatories (Pavlovsk/Slutsk and Voyeykovo) in 1878–1954. Geomagnetic disturbances were earlier divided by the compilers of paper catalogs (Benkov and Kalinin, 1941; *Handbook on the Variable Magnetic Field*, 1954; Afanas'eva and Bychkova, 1979) to Ssc and Sg storms and additionally ranked by the maximal amplitude of deviations of the declination D (Rd) and the horizontal H (Rh) and vertical Z (Rz) components, in nT: (1) moderate storm: $35 < \mathrm{Rd} \le 70$, or $150 < \mathrm{Rh} \le 300$, or $150 < \mathrm{Rz} \le 300$; (2) strong storm: $70 < \mathrm{Rd} \le 115$, or $300 < \mathrm{Rh} \le 500$, or $300 < \mathrm{Rz} \le 500$; (3) very strong storm: $\mathrm{Rd} > 115$, or $\mathrm{Rh} > 500$.

Data on the annual number of magnetic storms of different types are given in Table 1. In total, 1317 magnetic storms were recorded for 1878–1954: 360 storms with a sudden commencement (Ssc) and 957 with gradual commencement (Sg). The classification of the same storms by three categories (moderate, strong, and very strong) gives the following results: 929 moderate, 252 strong, and 136 very strong storms occurred during the studied period. Thus, Sg storms constituted 73% of those in the first half of the 20th century. This agrees well with the estimate of 76% made (Obridko et al., 2013) for magnetic storms recorded at IZMIRAN (Moscow) for the second half of the 20th century (1954–2000). The percentage of moderate storms in our data set is 70%.

Solar activity is characterized by the relative Wolf number W, which is the number of sunspots and their groups (SILSO data/image, Royal Observatory of Belgium, Brussels, http://www.sidc.be/silso/datafiles).

3. LONG-TERM TREND

Figure 1 shows the time variations in the number N of different storm types during 1878–1954 (cycles 12–18), as well as the aa index of geomagnetic activity. The upper panel shows the agreement between the curves of the total number of magnetic storms N and the aa index. It can be seen that, starting from 1900, N systematically increases for all storm types, which confirms the earlier results about the increase in the geomagnetic activity in the first half of the 20th century expressed by the aa index. This increases the number of both Sg and Ssc storms. It is interesting that the analysis carried out (Obridko et al., 2013) for storms in

1950–2000 revealed an increase in Sg storms but not in the Ssc storms in that period.

The upper panel in Fig. 1 clearly shows the previously known feature, i.e., the lag between the geomagnetic and solar activities (Love, 2011). However, the curves in the middle panel in Fig. 1 indicate that this is a feature of Sg, but not Ssc, storms. Since Sg storms make ~70% of the total number, their features significantly contribute into the behavior of the total number of storms.

In cycles 12–14 (1878–1900), the total number of storms at the cycle minima, the so-called “floor” (Kirov et al., 2013), is constant and close to zero, but it has been considerably growing since 1900 (Fig. 1, top panel). This growth is provided by an increase in the number of Sg storms at the cycle minima. In contrast to Sg storms, the number of Ssc storms in the minima of the cycles does not increase and is negligible.

Next, we compare the temporal trend in the number *N* of two storm types, Ssc and Sg, based on the total number of these storms in each solar cycle, *N*/cycle. The left panel of Fig. 2 shows the *N*/cycle and W/cycle of all storms (Ssc and Sg). In the right panel of Fig. 2, the percentages of Ssc and Sg storms of the total number of storms in each of the cycles under study are shown in the form of a histogram. It is seen in the left panel in Fig. 2 that the *N*/cycle for the total number of storms increases starting from cycle 14 for the both storms types. The number of Sg storms increased from 119 in cycle 14 to 171 in cycle 18; the number of Ssc storms increased from 30 in cycle 14 to 88 in cycle 18.

A characteristic feature of the increase in the *N*/cycle in cycles 14–18 is a specific structure superimposed on this increase for the total number of storms and for Sg storms, i.e., a low increase in even and high increase in odd cycles. Such asymmetry of solar cycles is observed in some solar and geomagnetic parameters that determine the 22-year variation (Gnevyshev and Ol, 1948; Chernosky 1966; Nagovitsyn et al., 2009). For Ssc storms, no such clear pattern is observed against the background of the general growth of *N*/cycle. However, it should be noted that the number of Ssc storms increases abruptly when changing from even to odd cycles (14/15 and 16/17) and insignificantly when changing from odd to even cycles (15/16 and 17/18).

Note that the number of Ssc storms in cycles 14–18 increases more rapidly than the of Sg storms: N_{SC} increased by 2.93 times, while N_{SG} increased by only 1.43 times (Fig. 2, left panel). Correspondingly, the contribution of these two types of storms in percent into the total number of storms varied with time. This is clearly seen in the right panel of Fig. 2: starting from cycle 13, the percentage of Sg storms fell from 86% to 66%, and the percentage of Ssc storms increased from 18% to 34%. Thus, in the first half of the 20th century, the contribution of Ssc storms into the geomagnetic activity almost doubled, while the contribution of Sg storms decreased by a factor of 1.5.

Table 1. Magnetic storms recorded at the observatories of St. Petersburg

Year	Total	Ssc	Sg
1878	6	3	3
1879	3	0	3
1880	10	1	9
1881	13	4	9
1882	24	6	18
1883	21	7	14
1884	12	6	6
1885	22	5	17
1886	20	2	18
1887	12	3	9
1888	14	2	12
1889	6	1	5
1890	3	0	3
1891	18	3	15
1892	31	8	23
1893	17	3	14
1894	23	4	19
1895	19	2	17
1896	24	2	22
1897	10	3	7
1898	16	3	13
1899	9	2	7
1900	6	2	4
1901	2	2	0
1902	2	1	1
1903	8	2	6
1904	10	0	10
1905	13	3	10
1906	11	1	10
1907	19	7	12
1908	21	5	16
1909	19	4	15
1910	25	3	22
1911	16	2	14
1912	3	0	3
1913	3	2	1
1914	7	1	6
1915	15	4	11
1916	24	5	19
1917	30	15	15
1918	31	5	26
1919	35	11	24
1920	31	6	25
1921	17	2	15
1922	23	1	22
1923	7	2	5
1924	9	1	8
1925	17	3	14
1926	28	9	19
1927	25	9	16
1928	23	7	16
1929	25	7	18
1930	28	11	17
1931	14	3	11
1932	17	5	12
1933	12	2	10
1934	11	5	6
1935	15	4	11
1936	17	7	10
1937	38	17	21
1938	41	20	21
1939	37	14	23
1940	30	10	20
1941	15	3	12
1942*	21	6	15
1943*	38	1	37
1944*	17	4	13
1945*	22	4	18
1946*	30	14	16
1947	29	14	15
1948	34	11	23
1949	24	13	11
1950	26	10	16
1951	32	8	24
1952	28	5	23
1953	19	4	15
1954	12	2	10

* The data are taken from the list of storms recorded simultaneously in Sverdlovsk (geographic latitude φ = 56.49° N, geomagnetic latitude Φ = 48.36° N), where the Slutsk Observatory was evacuated during the war (φ = 59.6° N, Φ = 56.14° N), as well as at the Srednikan, Yuzhno-Sakhalinsk, Tashkent, and Irkutsk Observatories (Reference Book on the Variable Geomagnetic Field, 1954; Afanas’eva and Bychkova, 1954). The latitudes of the Sverdlovsk and Slutsk Observatories are very close. In addition, the prewar lists of storms in the Reference Book and the Catalog of the Slutsk Observatory are in good agreement.

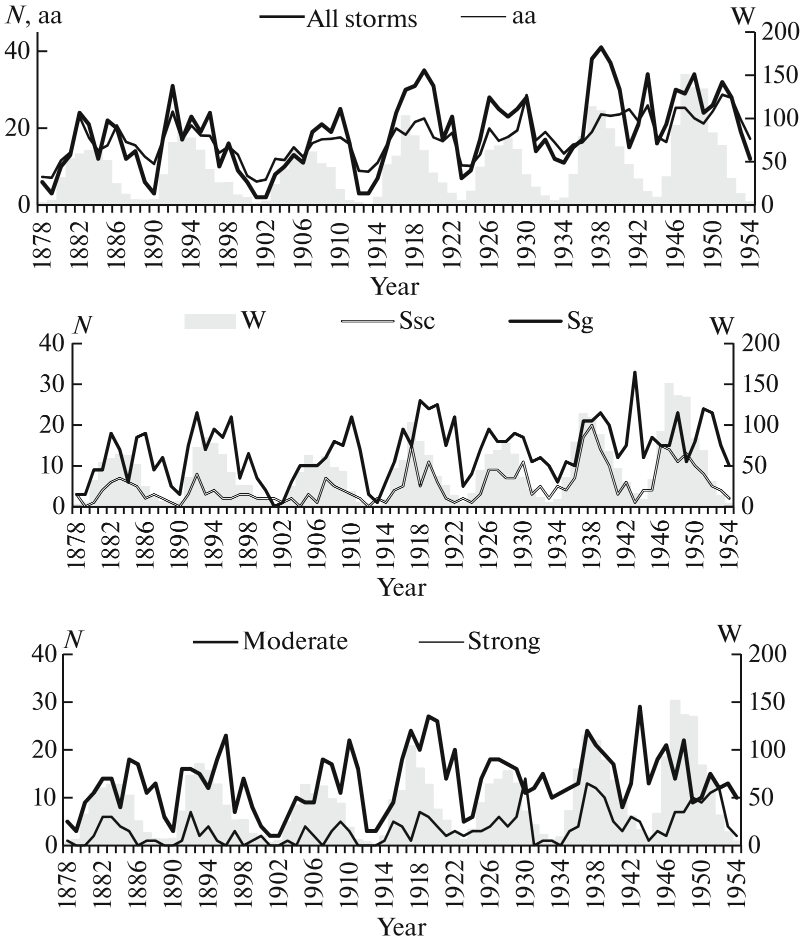

Fig. 1. Variations in the solar and geomagnetic activity. The gray histogram is the Wolf numbers W. (Upper panel) the total number of storms *N* (heavy curve) and aa index (thin curve); (middle panel) Ssc (heavy curve) and Sg storms (thin curve); (bottom panel) moderate (heavy curve) and strong storms (thin curve).

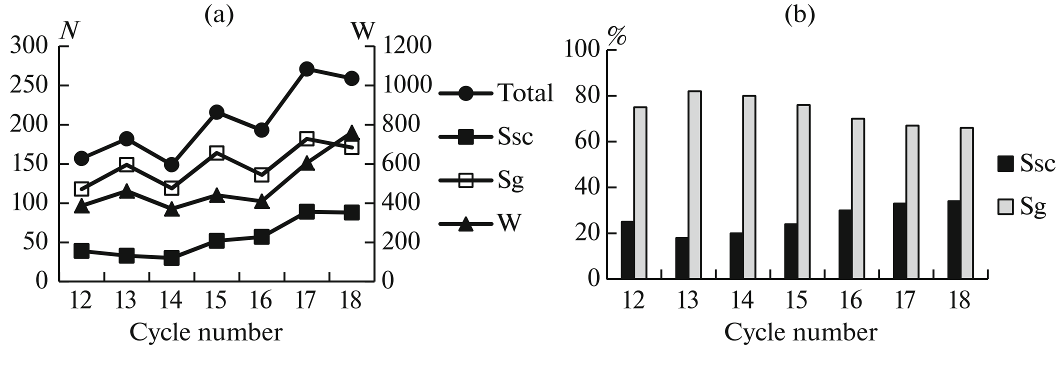

Fig. 2. Number of storms in solar cycles 12–18: (left panel) W and *N* for the total number of different storm types per a solar cycle; (right panel) the total numbers of Ssc and Sg storms as percentages of the total number of storms.

4. SEASONAL VARIATION

Let us now study the annual variation in the number of storms obtained by the epoch folding method for different storm types. Figure 3 shows the number of storms *N* observed in each month, summed over 76 years (1878–1954). The dashed lines show the region where the monthly total values of *N* differ from the annual arithmetic mean by less than a standard deviation ±σ; the standard errors are also shown. The standard deviation is calculated as $\sigma = \sqrt{(1/n)\sum_i (N_i - N_\mathrm{m})^2}$, where n is the sample size, i is the month number, N_i is the total value of *N* in the *i*th month, and N_m is the annual

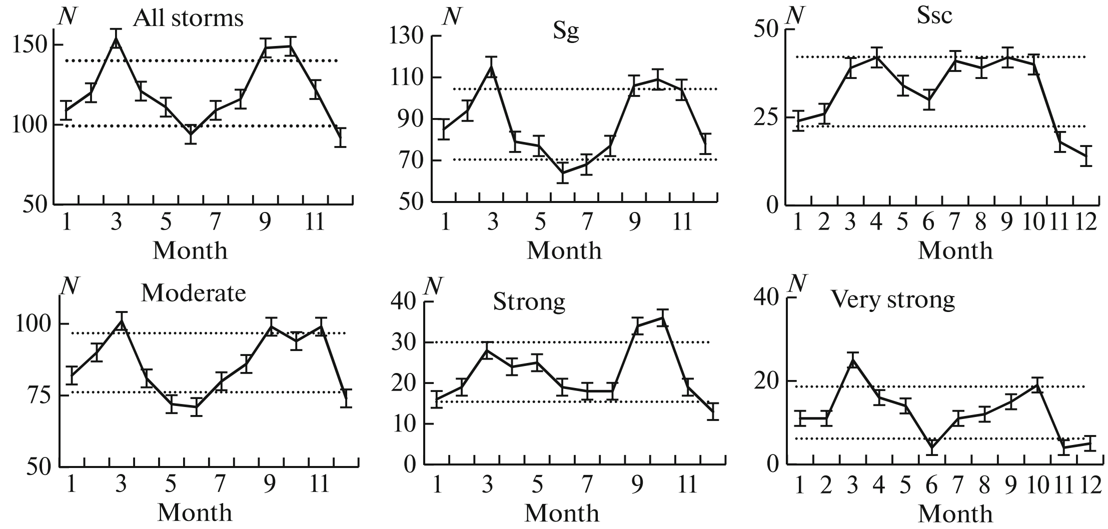

Fig. 3. Distribution of the number of magnetic storms *N* over months summed over 76 years (1878–1954). The area where monthly values differ from the annual arithmetic mean by less than a standard deviation is between two dashed lines.

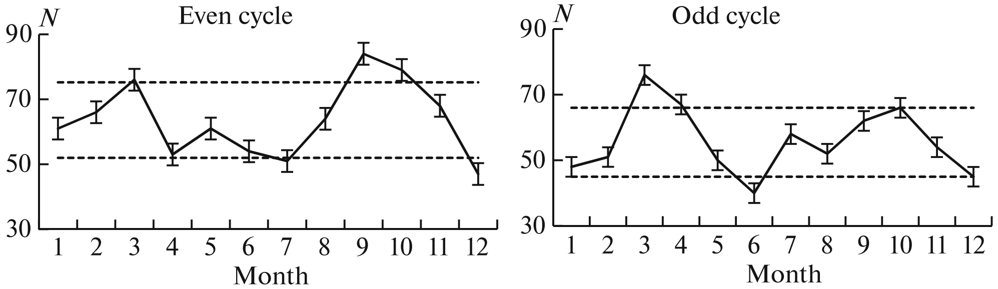

Fig. 4. Distributions of the total number of magnetic storms *N* over months summed separately over all even and odd cycles for 1878–1954. The area where monthly values differ from the annual arithmetic mean by less than a standard deviation is between two dashed lines.

arithmetic mean; the summation is performed over i from 1 to 12.

The total number of occurrence of magnetic storms *N* shows the expected semiannual variation with peaks in vernal and autumnal equinoxes (Fig. 3). However, it can be seen that this seasonal effect is weak, which agrees with the conclusions from the analysis of magnetic storms from IZMIRAN data for the second half of the 20th century (Obridko et al, 2014). Maxima with deviations of 2σ are detected only in the subplots for strong (in October) and very strong storms (in March). The second maxima deviate by a value less than σ in both cases. This is consistent with the result (Legrand and Simon, 1985) in which a deviation of +2σ was found for extremely strong storms only in March.

It was repeatedly noted earlier that the half-year variation in the geomagnetic activity (aa index) is the most typical for very strong storms (Russel and McPherron, 1973; Gonzalez et al., 1994). For our set of storms, the variation with two maxima in the periods of equinoxes is the most pronounced for moderate and Sg storms and, as a consequence, for the total number of storms (Fig. 3), with characteristic sharp spring (March) and wide autumn (September–November) maxima and a pronounced minimum in the periods of the summer and winter solstices. However, this effect does not reach 2σ. The number of Ssc storms also slightly increases in spring and autumn.

Next, we trace the dependence of the seasonal variation on the solar cycle parity/oddness. Attempts to detect such a dependence and thus the dependence on the polar magnetic field of the Sun were made in recent years, and the results were contradictory (Val'chuk, 2006, Ohand Yi, 2011, Mursula et al., 2011).

Figure 4 shows the distribution of the total number of magnetic storms over months, summed separately for even and odd cycles. The tendency to have two maxima (in vernal and autumnal equinoxes) is evident in the number of storms *N* both for even and odd cycles. However, in the region where the difference from the arithmetic mean exceeds the standard deviation, asymmetry in the geomagnetic activity in the first and second half of the year is observed: there is only an autumn maximum (September) in the total number of storms in even cycles and only a spring (March) maximum in odd cycles. Such a dominance of the only maximum in the occurrence of storms can be interpreted as the presence of annual waves, which, when summed, give the well-known semiannual wave (Mursula et al., 2011). However, the annual waves found by us are opposite in phase to the annual waves that were obtained (Mursula et al., 2011) during the study of substorms in cycles 23 and 24 (spring maximum for even and autumn maximum for odd cycles). It should be noted that the annual waves found in that work were not in the number of substorms but in their amplitude.

5. CONCLUSIONS

In this work, variations of the geomagnetic activity in terms of the annual number of magnetic storms *N* have been investigated. The analysis has shown the following.

—Numerical growth of *N* has been observed for all storm types since 1900, but the number of storms with the sudden commencement Ssc grew faster than the number of storms and the gradual commencement Sg.

—The contribution of Ssc and Sg storms in percent of the total number of storms varied with time. The percentage of Ssc storms almost doubled in the first half of the 20th century, while the percentage of Sg storms decreased by ~ 1.5 times.

—For Sg storms and, correspondingly, for the total number of storms, low even and high odd cycles are observed. Thus, a 22-year wave in *N* is observed for the total number of storms and Sg storms and is vague for Ssc storms.

—The expected seasonal variation with peaks in vernal and autumnal equinoxes is particularly evident for moderate and Sg storms.

—The tendency to have two equinoctial maxima in the total number of storms *N* is obvious both for even and odd cycles. However, the maximum of the total number of storms beyond the standard deviation is observed only in September in even cycles and in March in odd ones.

Ssc magnetic storms are driven by coronal mass ejections, and Sg storms are driven by corotating solar wind flows. The sources of CMEs and corotating flows are associated with different magnetic structures on the Sun: CMEs are connected with local closed magnetic fields, and corotating flows are associated with global fields with open lines of force and coronal holes. Our result apparently indicates that the activity of both types of solar magnetic structures were growing in 1900–1954 but that growth was more rapid for closed magnetic fields than for open ones.

The 22-year wave, which is observed in the total number of storms and Sg storms, can be associated with changes in the polarity of the polar magnetic field of the Sun. It is exactly the polar magnetic fields that mainly determine the behavior of high-speed flows responsible for Sg storms. A 22-year variation was found in the area of the polar zone of the Sun occupied by the unipolar magnetic field (Makarov et al., 2002); it manifested itself in an alternation of its increase and decrease in successive solar cycles.

The derived dependence of the seasonal variation in the total number of storms on the parity/oddness of solar cycle and, correspondingly, the presence of the 22-year wave can also be related to the sign of the polarity of the total magnetic field of the Sun.

The 22-year variation in different parameters of the geomagnetic activity is usually explained by Russell–McPherron effects and the Rosenberg–Coleman polarity effect, which are caused by different mutual arrangement of solar and terrestrial dipoles in different periods of the year (Rosenberg and Coleman, 1969; Russel, 1973, 1974; Russell and McPherron, 1973; Svalgaard, 1977). These are purely geometric effects. An alternative point of view (Cliver et al., 1996; Apostolov et al., 2004) assumes the effect of an internal solar source varying with a period of 22 years. Our results can apparently be evidence of a contribution from the internal source to the 22-year variation. The internal source on the Sun remains unclear.

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