ISSN 0016-7932, Geomagnetism and Aeronomy, 2013, Vol. 53, No. 2, pp. 147–156. © Pleiades Publishing, Ltd., 2013.
Original Russian Text © V.N. Obridko, Kh.D. Kanonidi, T.A. Mitrofanova, B.D. Shelting, 2013, published in Geomagnetizm i Aeronomiya, 2013, Vol. 53, No. 2, pp. 157–166.

Solar Activity and Geomagnetic Disturbances

V. N. Obridko, Kh. D. Kanonidi, T. A. Mitrofanova, and B. D. Shelting

Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Russian Academy of Sciences (IZMIRAN), Troitsk, Moscow oblast, 142190 Russia

e-mails: obridko@izmiran.ru; kanonidi@izmiran.ru; tamara_m@izmiran.ru; shelting@izmiran.ru

Received August 23, 2011; in final form, December 14, 2011

Abstract—An analysis of IZNIRAN magnetic observatory data indicated that geomagnetic storms with sudden and gradual commencements form two independent populations with respect to the disturbance occurrence time and character because the solar sources of these disturbances are different. Storms with sudden and gradual commencements are caused by coronal mass ejections and high-speed solar wind streams from coronal holes, respectively.

DOI: 10.1134/S0016793213010143

1. INTRODUCTION

The aim of this work is to study the distribution of magnetic storms with gradual and sudden commencements (1950–2010) during five solar activity cycles. In addition, it is to a certain degree interesting to consider the annual variations (distribution over months) in magnetic storms of different origins.

The task of this work is to specify the features of different magnetic disturbances in order to determine the interrelationship between solar activity cycles. We also had to determine the seasonal variations in magnetic storms and their singularities.

It is known that two geomagnetic sources exist (Legrand and Simon, 1981, 1989; Venkatesan et al., 1982, 1991; Feynman, 1982; Simon and Legrand, 1989; Gonzalez et al., 1990; Echer et al., 2004). One of the sources (coronal mass ejections or CMEs) more or less agrees with solar cycle variations since it is related to strong closed local fields characterized by the sunspot number, which is the most well-known index. High-speed solar wind streams are the second source. They are related to coronal holes, which largely depend on large-scale and global magnetic fields. Large-scale fields also follow the 11-year cycle; however, their maximum is displaced relative to the sunspot cycle maximum (Obridko and Shelting, 1992, 1999; Tlatov and Makarov, 2005; Nagovitsyn, 2006; Obridko et al., 2009, 2011). In many cycles, geomagnetic disturbances reach the maximal occurrence slightly later than the sunspot number maximum is formed (Svalgaard, 1977; Legrand and Simon, 1981, 1985; Sargent, 1985; Simon and Legrand, 1989; Tsurutani et al., 1995, 2006; Wang et al., 2000; Richardson et al., 2002; Schwenn, 2006).

Geomagnetic disturbances are also divided into two types: storms with gradual and sudden commencements. In the present work, we will indicate that the difference between these disturbances consists in that they are related to different solar agents and therefore form uncorrelated populations independent of each other.

2. DATA

Our statistical analysis was based on the data of the geomagnetic observatory for 1950–2010.

All data on the geomagnetic field were obtained at IZMIRAN. Data on solar activity were obtained from special literature and the Internet. Data on coronal mass ejections were taken from the catalog presented in (Gopalswamy et al., 2010). Information on coronal holes was obtained from the Jaan Alvestad site Coronal Hole History (since Late October 2002) and directly from EUV observations on the SOHO space station for an earlier period (Obridko et al., 2011).

3. COMPARISON OF THE MAGNETIC STORM OCCURRENCE WITH THE SUNSPOT NUMBER

All initial data are presented in Tables 1 and 2.

During the considered period occurred 2607 geomagnetic disturbances of different intensities and character. It turned out that 614 storms (i.e., 24%) had sudden commencements. The remaining 1993 storms (76%) had gradual commencements. Thus, the number of storms with sudden commencement was three times as small as that of storms with gradual commencement. But the number of large and very large storms in the first and second groups considered by us is almost identical.

An analysis indicated that the number of magnetic storms with sudden commencement increases in proportion with an intensification of solar activity and

Table 1. Magnetic storms of different types (1950–2010)

Year	Number of storms			Number of sunspots	Year	Number of storms			Number of sunspots
	Total	Storms with SC	Storms with GC			Total	Storms with SC	Storms with GC	
1950	32	19	13	83.9	1981	46	26	20	140.5
1951	59	52	7	69.4	1982	73	59	14	115.9
1952	51	46	5	31.5	1983	64	50	14	66.6
1953	29	29	0	13.9	1984	56	51	5	45.9
1954	23	22	1	4.4	1985	37	33	4	17.9
1955	27	23	4	38.0	1986	35	31	4	13.4
1956	50	32	18	141.7	1987	35	32	3	29.2
1957	53	29	24	190.2	1988	46	38	8	100.2
1958	47	31	16	184.8	1989	67	37	30	157.6
1959	43	25	18	159.0	1990	41	25	16	142.6
1960	58	42	16	112.3	1991	53	38	15	145.7
1961	47	36	11	53.9	1992	43	33	10	94.3
1962	41	36	5	37.6	1993	47	39	8	54.6
1963	21	18	3	27.9	1994	54	50	4	29.9
1964	27	23	4	10.2	1995	53	49	4	17.5
1965	20	13	7	15.1	1996	26	26	0	8.6
1966	30	19	11	47.0	1997	30	21	9	21.5
1967	38	25	13	93.7	1998	43	38	5	64.3
1968	40	30	10	105.9	1999	59	43	16	93.3
1969	31	17	14	105.5	2000	72	47	25	119.6
1970	28	11	17	104.5	2001	58	37	21	111.0
1971	28	17	11	66.6	2002	63	45	18	104.0
1972	33	23	10	68.9	2003	109	93	16	63.7
1973	44	42	2	38.0	2004	55	42	13	40.4
1974	37	32	5	34.5	2005	63	53	10	29.8
1975	34	31	3	15.5	2006	40	37	3	15.2
1976	30	28	2	12.6	2007	33	30	3	8.0
1977	31	26	5	27.5	2008	27	25	2	3.0
1978	45	27	18	92.5	2009	7	7	0	3.1
1979	35	12	23	155.4	2010	25	22	3	16.5
1980	35	20	15	154.6	Total	2607	1993	614	

Table 2. Distribution of the number of magnetic storms over months (1950–2010)

Month	Storms with SC	Storms with GC	All storms
I	180	34	214
II	163	54	217
III	179	59	238
IV	164	62	226
V	160	56	216
VI	148	53	201
VII	150	54	204
VIII	145	60	205
IX	184	52	236
X	198	56	254
XI	171	43	214
XII	151	31	182
Total	1993	614	2607
Average monthly value	217.25	51.17	166.08
Rms deviation from the average	19.22	9.96	16.60

Table 3. Characteristics of magnetic storms

Storm characteristic	*D*	*H*	*Z*
Small	100–139	80–125	40–90
Moderate	140–200	126–200	91–140
Large	201–290	201–270	141–250
Very large	≥291	≥271	≥251

Note: *D*, *H*, and *Z* are the magnetic declination and the horizontal and vertical geomagnetic field components, respectively.

their maximums completely coincide. This is demonstrated by Fig. 1a.

Solar activity cycles for 1950–2010 and a plot of geomagnetic storms with sudden commencement during the same period are shown here.

The behavior of storms with gradual commencement is different. Their maximum is formed two to three years after the formation of a solar activity maximum (Fig. 1b).

We can calculate the correlation between the appearance of these two storm types and the sunspot number. The correlation coefficient between storms with sudden commencement and the sunspot number is rather large (0.872 ± 0.06). The correlation coefficient between storms with gradual commencement and the sunspot number is on the contrary very small and is virtually zero (0.014 ± 0.13). However, the correlation coefficient is increasing if we construct a correlation function by shifting the sunspot number plot forward (see Fig. 2).

If the shift is three years, the correlation coefficient reaches its maximum and is 0.41 ± 0.12.

Figure 3 shows regression plots for storms with sudden commencement (open circles) without a shift and for storms with gradual commencement (filled circles) at a shift of three years. The numbers of sunspots are shown along the abscissa.

We should pay attention to the fact that the angular coupling coefficients almost coincide on the diagrams. They are 0.115 and 0.119 for storms with gradual and sudden commencements, respectively. This difference is statistically insignificant and indicates that the mechanisms by which oncoming solar wind streams interact are identical in both cases. Differences between these two storm types (namely: occurrence frequency, time shift, and disturbance profile) depend on the properties of solar agents responsible for their occurrence.

4. TWO STORM TYPES: DIFFERENT POPULATIONS

In this section, we will compare the occurrence frequency of different-power storms with the sunspot number. The magnetic storm value was determined in

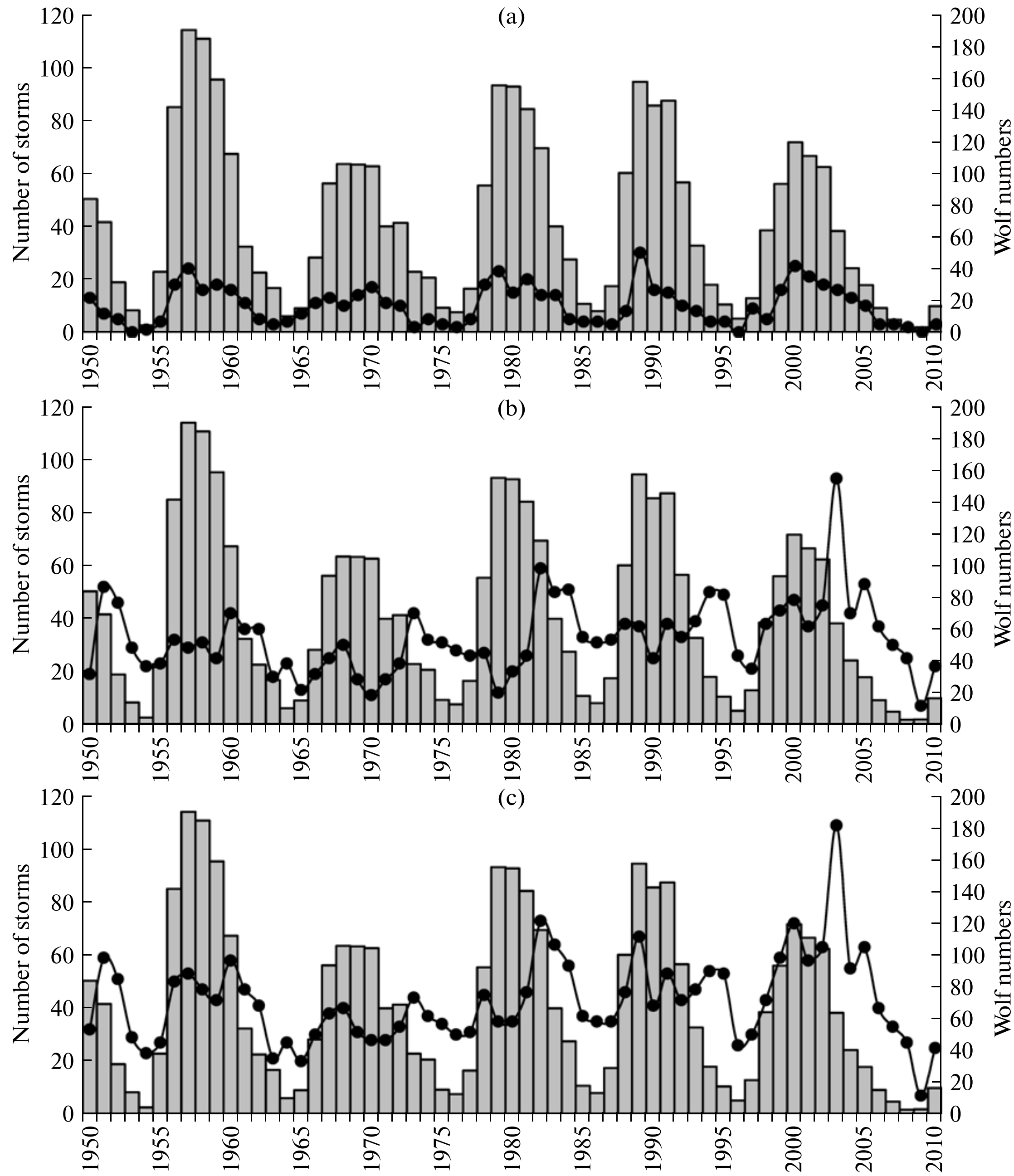

Fig. 1. Distribution of magnetic storms over years (1950–2010): (a) storms with SC, (b) storms with GC, and (c) all storms.

nanoteslas (10^{-5} oersted), according to the regulations of the International Committee, for the parameters shown in Table 3.

All (strong, moderate, and weak) storms with sudden (Fig. 4, solid curves) and gradual (Fig. 5, solid curves) commencements are compared with the sunspot number (dashed line) in Figs. 4 and 5. To simplify the consideration and increase the statistics, we combined strong and very strong storms in one class. A comparison of Figs. 4 and 5 indicates that storms with all intensities follow the rule formulated by us above: storms with sudden commencement are in good agreement with the sunspot number curve, and storms with gradual commencement are shifted by one to three years. In this case, the number of strong storms of both types is approximately identical; however, the number of moderate and weak storms with gradual commencement is much larger than a number of storms with sudden commencement of the same power.

It is interesting that the plots show a smooth increase in geomagnetic activity with gradual com-

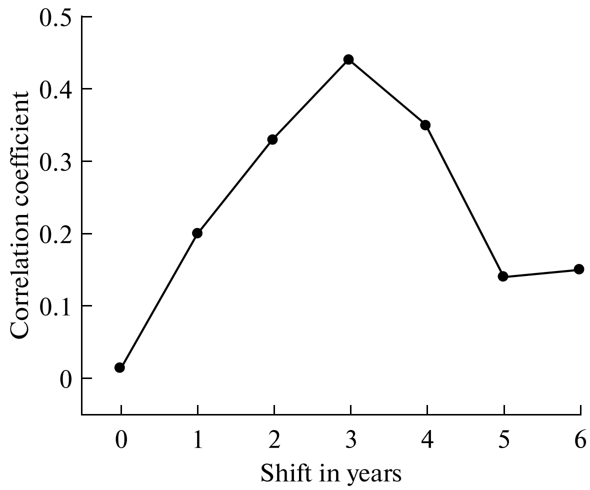

Fig. 2. Cross-correlation function for average annual values of sunspots and numbers of storms with GC. The shift in years is shown on the abscissa.

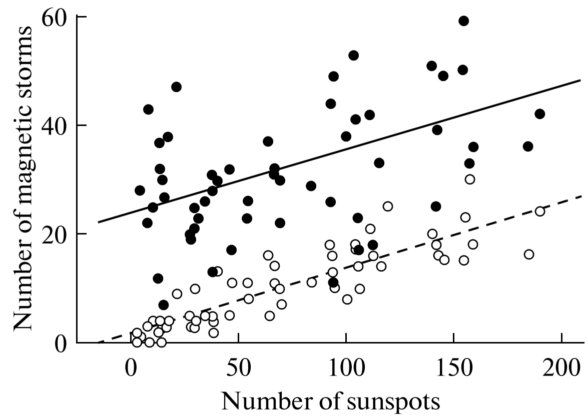

Fig. 3. Regressions of storms with SC (open circles) without a shift and storms with GC (filled circles) at a shift of three years. The numbers of sunspots are shown on the abscissa.

mencement in the course of time, previously indicated in (Kishcha et al., 1999). In this case, this increase completely depends on an increase in the number of weak storms with gradual commencement and is completely absent in storms with sudden commencement.

To study the relationship between the occurrence of different storm types with different magnitudes, we calculated their cross correlation. It turned out that the correlation within either type of storms is very high. For storms with gradual commencement, the correlation between the total list of all storms and storms with different magnitudes is 0.84, 0.78, and 0.62 for weak, moderate, and strong storms, respectively. For storms with sudden commencement, the correlation between the total list of all storms and storms with different magnitudes is 0.78, 0.88, and 0.82 for weak, moderate, and strong storms, respectively. But the internal correlation between the occurrence frequencies of the weakest and strongest storms decreases slightly, it is 0.24 and 0.37 for storms with gradual and sudden commencements, respectively.

A complete absence of correlation between occurence of storms with gradual and sudden commencements is of prime importance for understanding the nature of these storms. The correlation coefficient is no more than 0.10 with an error of 0.15. Thus, storms of these types form two independent populations, which is undoubtedly is determined by a different nature of solar agents exciting storms.

5. SEASONAL VARIATIONS

At the next stage of analysis, we distributed the number of the studied storms over months. We constructed the corresponding plots (see Table 3; Figs. 6a–6c). It is known that the relative position of the Earth's magnetic dipole axis and the average IMF direction change systematically during a year, as a result of which the geoeffectiveness of solar wind disturbances changes. Therefore, a semiannual wave, with maximums near the spring and autumnal equinoxes and minimums in June and December near the summer and winter solstices, is observed in geomagnetic activity.

Figure 6 shows the distribution of magnetic storms occurrens over months (1950–2010) divided by monthly mean for the entire period. The region where the observed occurrence frequency values differ from the mean uniform value by less than one rms deviation (σ) is shaded. It is evident that the effect of an increase in the number of magnetic storms during the autumnal equinox months is actually observed but is rather weak (close to being unreliable). Only storms with gradual commencement (and, as a consequence, all storms) in October have a maximum ($\sim 2\sigma$). For storms with sudden commencement, the maximum in April is very feeble and the minimum in December–January is clearly defined. Legrand and Simon (1985) confirmed the effect based on an analysis of especially strong storms in 1868–1980. However, in their work, a positive deviation ($\sim 2\sigma$) from the average is only reached in March, and the negative deviation (1.5σ) is substantially smaller in June and December.

It is unclear why the seasonal effect is so insignificant. Possibly, its value is in general overstated in literature. However, this effect possibly depends on the polarity of the general solar magnetic field (Obridko et al., 2002, 2004). In such a case, we cannot at all consider the seasonal effect by averaging data over several cycles at once. It is necessary to take into account polarity reversals of the general magnetic field and to combine the years when the general solar magnetic field had the same sign.

On the other hand, we should note that the occurrence frequency seasonal curves are sharply different for storms with gradual and sudden commencements.

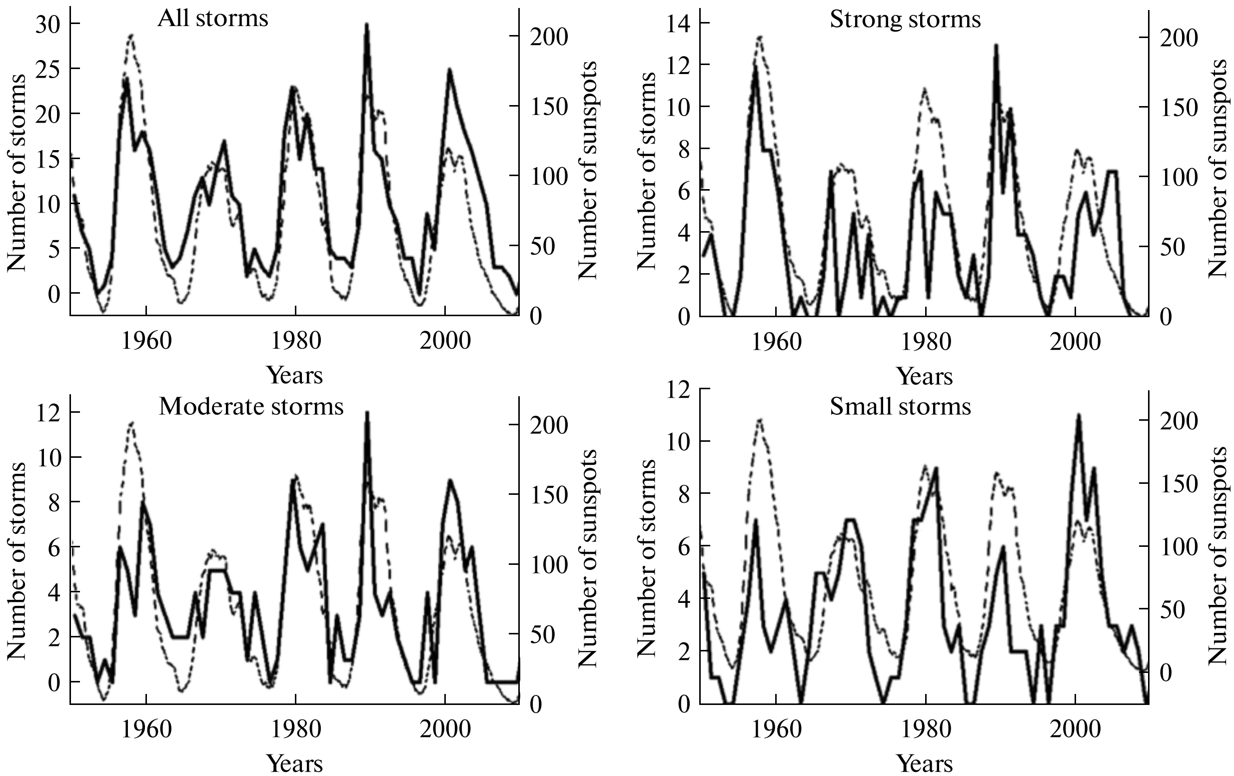

Fig. 4. Annual number of all storms and strong, moderate, and weak storms with SC (solid curves) as compared to the number of sunspots (dashed line).

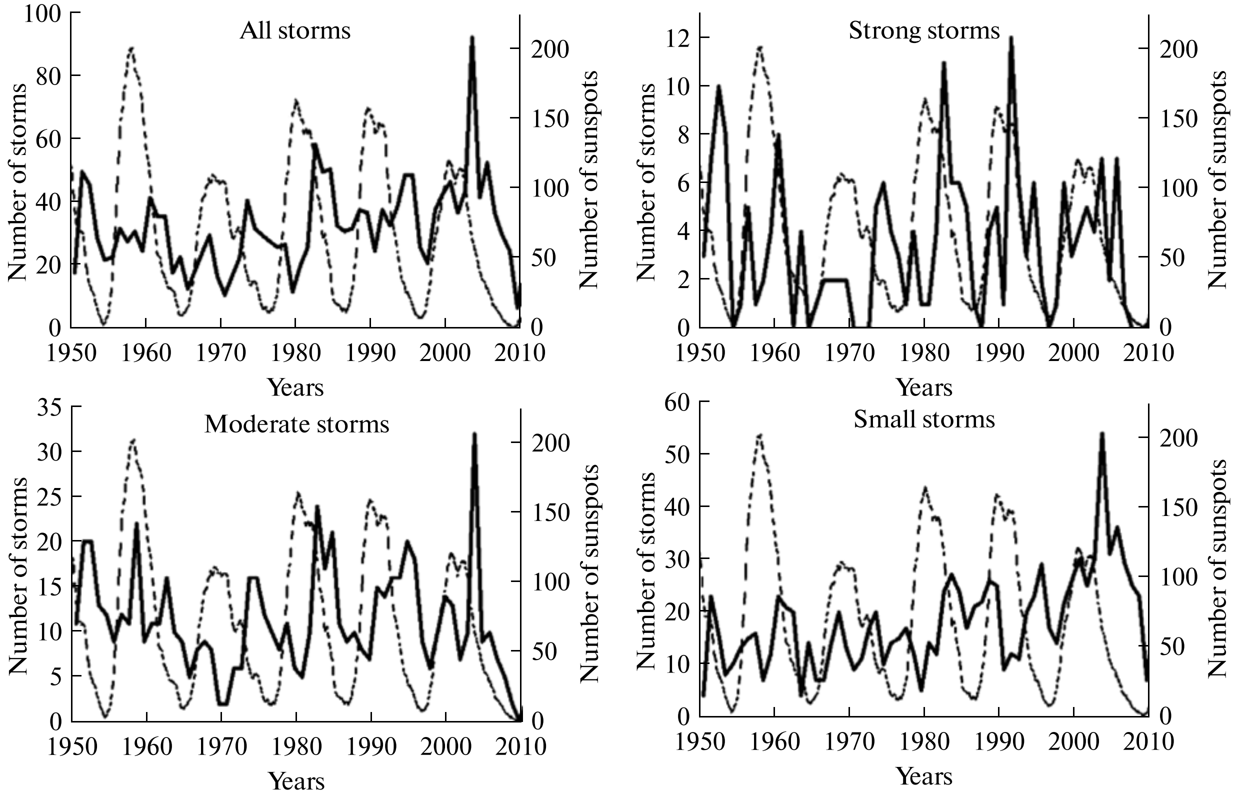

Fig. 5. Annual number of all storms and strong, moderate, and weak storms with GC (solid curves) as compared to the number of sunspots (dashed line).

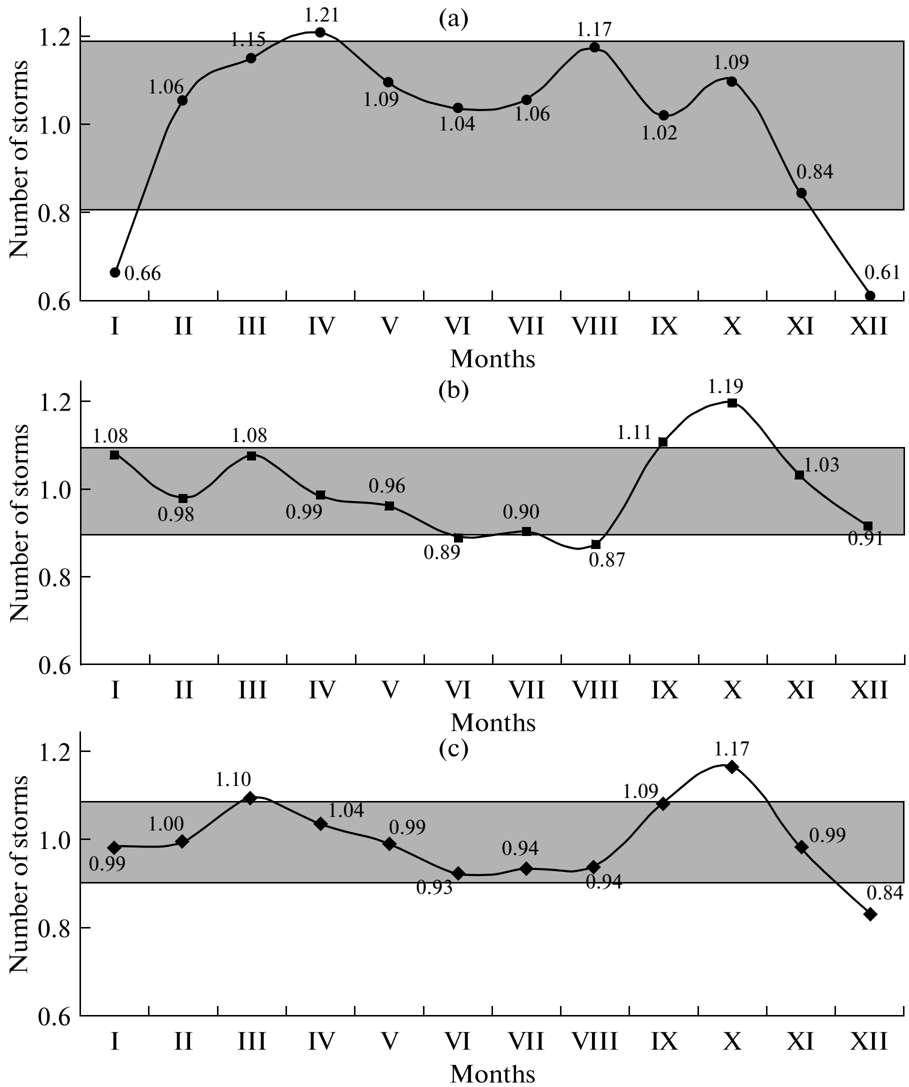

Fig. 6. Distribution of magnetic storms over months (1950–2010) divided by monthly mean for entire period: (a) storms with SC, (b) storms with GC, and (c) all storms.

The correlation coefficient between these curves is 0.016 ± 0.29, i.e., being strictly zero. This emphasizes once more that these two storm types are different and directly indicates that the solar agents responsible for their appearance are different.

6. SOLAR AGENTS: CORONAL HOLES AND CORONAL MASS EJECTIONS

Geoeffective solar agents are various but can be conditionally divided into two groups. Coronal mass ejections are often related to flares and represent a magnetic cloud that approaches the Earth at a relatively high velocity (600–1000) km/s. These ejections usually have a sharp leading front and result in the origination of magnetic storms with sudden commencement (SC). Since these agents are more frequently related to active regions on the Sun (the so-called local magnetic fields), we can anticipate (and this is confirmed by statistics) that the correlation between storms with SC and the sunspot number is high. High-speed solar wind streams propagate at a velocity of 450–700 km/s and result in the origination of storms with gradual commencement. They are related to solar coronal holes, which reach their maximal development 5–6 years after the sunspot number maximum. Therefore, we can anticipate (and this is confirmed by statistics) that the number of storms with gradual commencement (GC) is shifted relative to the sunspot numbers by a half cycle.

Figure 7 shows the distribution of coronal mass ejections, sunspot number, and storms with SC over years in cycle 23. Figure 7 is based on data from (Gopalswamy et al., 2010), but the data of only two catalogs, which are considered to be the most reliable ones, were used: the catalog prepared by the Coordi-

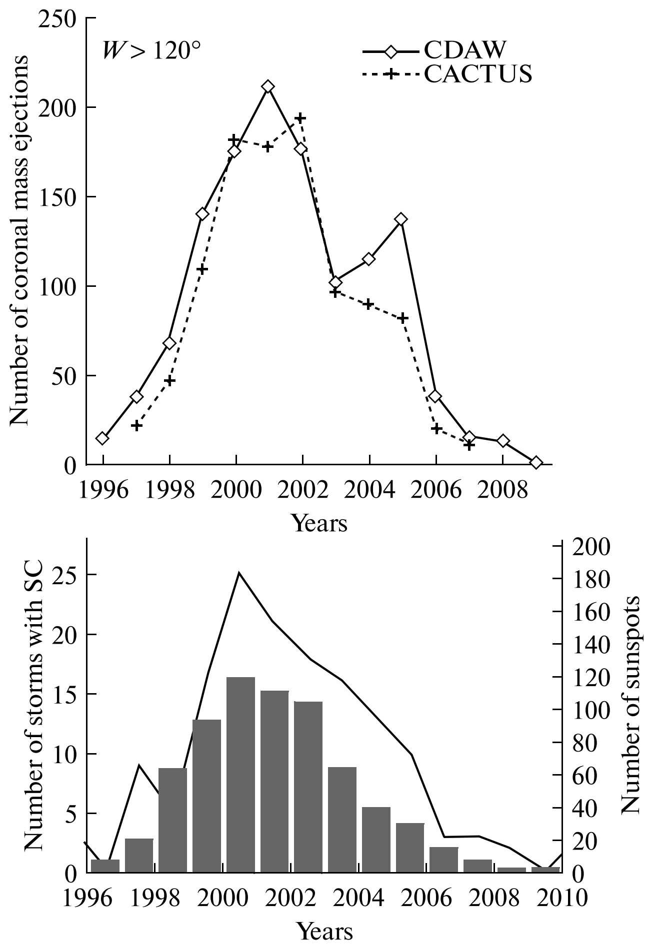

Fig. 7. Distribution of coronal mass ejections, sunspot number, and storms with SC over years in cycle 23.

nated Data Analysis Workshop (CDAW) and the *Computer-Aided CME Tracking* (CACTus) catalog (Robbrecht and Berghmans, 2004). A solid line on the lower panel in Fig. 7 shows the distribution of the occurrence of storms with SC over years and the sunspot number distribution as a histogram. The coincidence of all three curves is evident.

Figure 8 shows a similar comparison of the distributions of coronal holes, sunspot numbers, and storms with GC. The similarity of these curves is doubtless; the correlation coefficient is 0.6 ± 0.17, although the number of magnetic storms decreases faster than that of coronal holes as a minimum is approached. This is possibly a specific feature of cycle 23, when the number of equatorial coronal holes was unusually large during the decline phase (Obridko and Shelting, 2009).

The secondary maximum in the occurrence frequency of strong storms three years after the sunspot number maximum was previously registered by Legrand and Simon (1985); however, these researchers did not relate this maximum directly to coronal holes, which were hardly known at that time. Tsurutani et al. (1995) assumed that this shift is related to cyclic variations in open solar magnetic fields and subsequently (Tsurutani et al., 2006) directly indicated that corotating flows are related to coronal holes.

7. CONCLUSIONS

An analysis, performed based on long series of uniform data, indicated that the manifestations of geomagnetic disturbances with sudden and gradual commencements are much different. Both disturbance types form two independent populations with respect to the disturbance occurrence time and character. The occurrence of these disturbance types differently depends on the season of the year because their solar sources are different, are differently localized on the solar disk, and show different cyclic variations. Storms with SC and GC are caused by coronal mass ejections

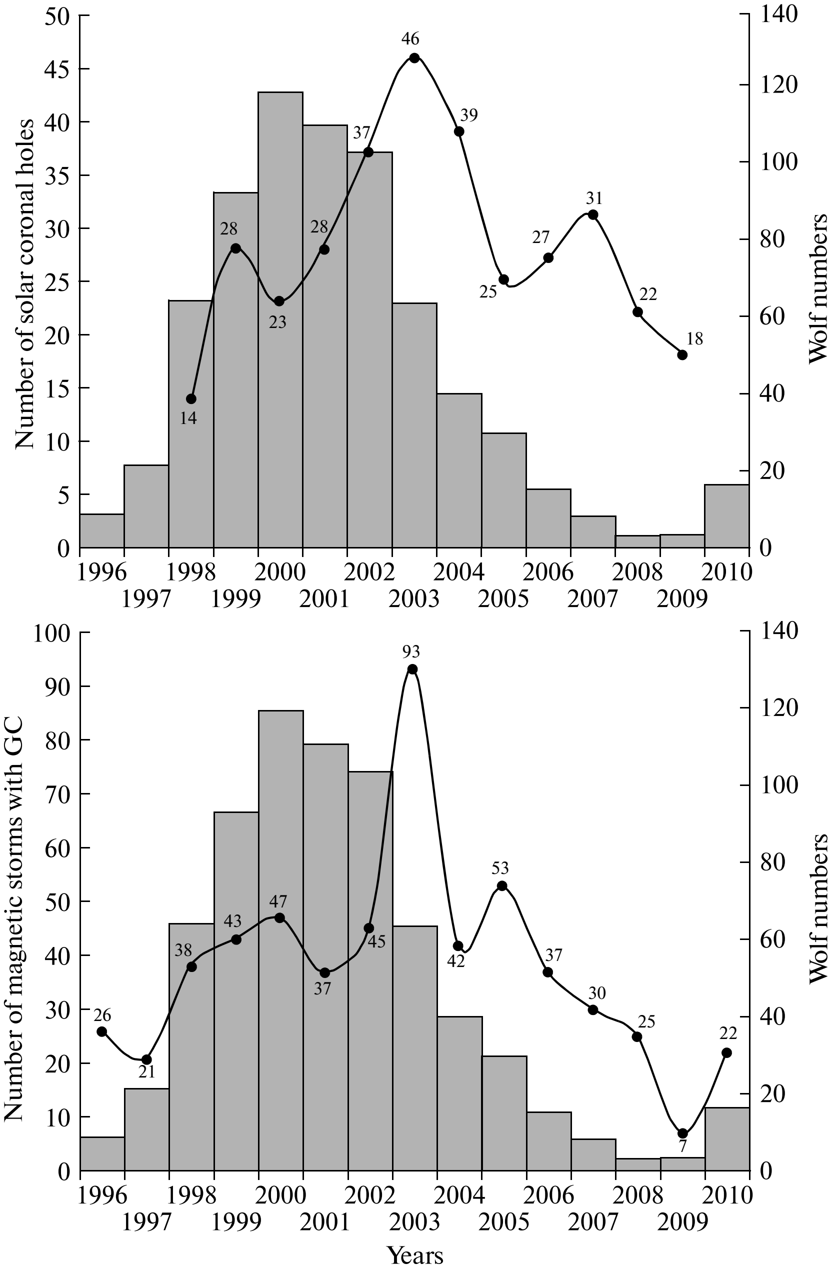

Fig. 8. Distribution of coronal holes, sunspot number, and storms with GC over years in cycle 23.

and high-speed solar wind streams from coronal holes, respectively. At the same time, the physical mechanisms by which solar agents interact with the Earth's magnetosphere are apparently identical.

REFERENCES

Echer, E., Gonzalez, W.D., Gonzalez, A.L.C., Prestes, A., Vieira, L.E.A., dal Lago, A., Guarnieri, F.L., and Schuch, N.J., Long-Term Correlation between Solar and Geomagnetic Activity, *J. Atmos. Sol.–Terr. Phys.*, 2004, vol. 66, no. 12, pp. 1019–1025.

Feynman, J., Geomagnetic and Solar Wind Cycles, 1900–1975, *J. Geophys. Res.*, 1982, vol. 87, pp. 6153–6162.

Gonzalez, W.D., Gonzalez, A.I.C., and Tsurutani, B.T., Dual-Peak Solar Cycle Distribution of Intense Geomagnetic Storms, *Planet. Space Sci.*, 1990, vol. 38, pp. 181–187.

Gopalswamy, N., Yashiro, S., Michalek, G., Xie, H., Mäkelä, P., Vourlidas, A., and Howard, R.A., A Catalog of Halo Coronal Mass Ejections from SOHO, *Sun Geosphere*, 2010, vol. 5, no. 1, pp. 7–16.

Kishcha, P.V., Dmitrieva, I.V., and Obridko, V.N., Long-Term Variations of the Solar–Geomagnetic Correlation, Total Solar Irradiance, and Northern Hemispheric Temperature (1868–1997), *J. Atmos. Sol.–Terr. Phys.*, 1999, vol. 61, no. 11, pp. 799–808.

Legrand, J.P. and Simon, P.A., Ten Cycles of Solar and Geomagnetic Activity, *Sol. Phys.*, 1981, vol. 70, no. 1, pp. 173–195.

Legrand, J.P. and Simon, P.A., Some Solar Cycle Phenomena Related to the Geomagnetic Activity from 1868 to 1980. Part 1. The Shock Events, or the Interplanetary Expansion of the Toroidal Field, *Astron. Astrophys.*, 1985, vol. 152, no. 2, pp. 199–204.

Legrand, J.P. and Simon, P.A., Solar Cycle and Geomagnetic Activity: A Review for Geophysicists. Part 2. The Solar Sources of Geomagnetic Activity and Their Links with Sunspot Cycle Activity, *Ann. Geophys.*, 1989, vol. 7, no. 6, pp. 579–593.

Nagovitsyn, Yu.A., Solar and Geomagnetic Activity on a Large Time Scale: Reconstructions and Prediction Possibilities, *Pis'ma Astron. Zh.,* 2006, vol. 32, no. 5, pp. 382–391.

Obridko, V.N. and Shelting, B., Cyclic Variation of the Global Magnetic Field Indices, *Sol. Phys.*, 1992, vol. 137, no. 1, pp. 167–177.

Obridko, V.N. and Shelting, B.D., Structure and Cyclic Variations of Open Magnetic Fields in the Sun, *Sol. Phys.*, 1999, vol. 187, no. 3, pp. 185–205.

Obridko, V.N. and Shelting, B.D., Certain Anomalies in the Evolution of Global and Large-Scale Solar Magnetic Fields as Precursors of Several Oncoming Low Cycles, *Pis'ma Astron. Zh.*, 2009, vol. 35, no. 3, pp. 38–44.

Obridko, V.N., Golyshev, S.A., and Levitin, A.E., Secular and Cycle Variations of the IMF *Bz* Component and Some Associated Geophysical Effects, *Proc. the SOLSPA 2001 Euroconference: Solar Cycle and Space Weather*, Vico Equence, 2001, pp. 404–407.

Obridko, V.N., Golyshev, S.A., and Levitin, A.E., Relation between the Structure of the Large-Scale Solar Magnetic Field in the Activity Cycles and IMF Governing Geomagnetic Activity, *Geomagn. Aeron.*, 2004, vol. 44, no. 4, pp. 449–452 [*Geomagn. Aeron.* (Engl. transl.), 2004, vol. 44, pp. 410–412].

Obridko, V.N., Shelting, B.D., Livshits, I.M., and Askerov, A.B., Relation between Coronal Hole Contrast and Solar Wind Characteristics, *Astron. Zh.*, 2009, vol. 86, no. 3, pp. 1125–1132.

Obridko, V.N., Shelting, B.D., and Livshits, I.M., Open Solar Magnetic Fields and Characteristics of the near-Earth Solar Wind, *Astron. Zh.*, 2011, vol. 88, no. 3, pp. 313–320.

Richardson, I.G., Cane, H.V., and Cliver, E.W., Sources of Geomagnetic Activity during nearly Three Solar Cycles (1972–2000), *J. Geophys. Res.*, 2002, vol. 107A, pp. 1187–1200.

Robbrecht, E. and Berghmans, D., Automated Recognition of Coronal Mass Ejections (CMEs) in Near-Real-Time Data, *Astron. Astrophys.*, 2004, vol. 425, no. 7, pp. 1097–1106.

Sargent, H.H., Recurrent Geomagnetic Activity - Evidence for Long-Lived Stability in Solar Wind Structure, *J. Geophys. Res.*, 1985, vol. 90, pp. 1425–1428.

Schwenn, R., Solar Wind Sources and Their Variations over the Solar Cycle, *Space Sci. Rev.*, 2006, vol. 124, nos. 1–4, pp. 51–76.

Simon, P.A. and Legrand, J.P., Solar Cycle and Geomagnetic Activity: A Review for Geophysicists. I - The Contributions to Geomagnetic Activity of Shock Waves and of the Solar Wind. II The Solar Sources of Geomagnetic Activity and Their Links with Sunspot Cycle Activity, *Ann. Geophys.*, 1989, vol. 7, no. 6, pp. 565–593.

Svalgaard, L., Geomagnetic Activity: Dependence on Solar Wind Parameters, in *Coronal Holes and High Speed Wind Streams in Coronal Holes and High Speed Wind Streams*, Zirker, J.B, Ed., Boulder: Colorado Ass. U. Press, 1977, pp. 371–441.

Tlatov, A.G. and Makarov, V.I., Indices of Solar Activity in Minimum of Sunspot Cycles, *Proc. Conf. Large-Scale Structures and Their Role in Solar Activity*, New Mexico, 2005, vol. 346, p. 415.

Tsurutani, B.T., Gonzalez, W.D., Gonzalez, A.L.C., Tang, F., Arballo, J.K., and Okada, M., Interplanetary Origin of Geomagnetic Activity in the Declining Phase of the Solar Cycle, *J. Geophys. Res.*, 1995, vol. 100A, pp. 21717–21734.

Tsurutani, B.T., Gonzalez, W.D., Gonzalez, A.L.C., et al., Corotating Solar Wind Streams and Recurrent Geomagnetic Activity: A Review, *J. Geophys. Res.*, 2006, vol. 111A, pp. 11 107–11 132.

Venkatesan, D., Shukla, A.K., and Agrawal, S.P., Cosmic Ray Intensity Variations and Two Types of High Speed Solar Streams, *Sol. Phys.*, 1982, vol. 81, pp. 375–381.

Venkatesan, D., Ananth, A.G., Graumann, H., and Pillai, S., Relationship between Solar and Geomagnetic Activity, *J. Geophys. Res.*, 1991, vol. 96, pp. 9811–9813.

Wang, Y.M., Lean, J., and Sheeley, N.R., The Long-Term Variation of the Sun's Open Magnetic Flux, *Geophys. Res. Lett.*, 2000, vol. 27, no. 4, pp. 505–508.

http://www.solen.info/solar/coronal_holes.html.