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THE PROBLEM OF THE GEOMAGNETIC ACTIVITY ASSESSMENT

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Abstract. Geomagnetic field disturbance scale is called geomagnetic activity and currently is described by special geomagnetic indices. Among them there are those referring to local geomagnetic disturbances (K–indices); those describing global geomagnetic field perturbations (Kp-index); indices indicating magnetic disturbance intensity caused by different current systems (Dst index follows the dynamics of the magnetospheric ring current, AE, AU, AL-indices show auroral electrojet dynamics, PC-index describes the electric field over the polar caps). Being introduced long time ago, these indices are not capable of describing the real geomagnetic activity on the Earth's surface for a day, a week, a month or a year. Undoubtedly, they are capable of reflecting temporal dynamics of geomagnetic field variations but they refer to great disturbances occurring only one tenth of the year. From geomagnetic activity indices, it is impossible to find the real quantitative proportion between geomagnetic activity levels in different intervals of magnetospheric disturbances. It is difficult to quantify the geomagnetic activity either. In our view, the real geomagnetic activity is described by total energy of geomagnetic variations distributed over the Earth's surface. The analysis of geomagnetic activity described by Kp-index shows that statistical maxima around equinocial months in the annual variation of Kp-activity are caused by the annual variation of magnetic storm numbers. During the main phase of magnetic storms, Kp-index observatories fix the magnetic field of auroral electrojets shifted southward to subauroral latitudes, which provides Kp-index high amplitudes. These high amplitudes cause activity maxima around equinocial months. The geomagnetic activity has been estimated from model calculation of the energy of large-scale geomagnetic variations with the use of the IZMEM model obtained from correlation of ground-based geomagnetic data with solar wind parameters. The annual variation of the geomagnetic activity averaged over 1996 – 2003 does not practically change during different seasons of the year. Model geomagnetic activity for different activity zones, such as the polar cap and the auroral oval, during major magnetic storms of October and November, 2003 has been discussed.

1. The problem of quantitative description of geomagnetic activity

The scale of geomagnetic field disturbance is called geomagnetic activity. At present, geomagnetic activity is described by special geomagnetic indices, which were introduced long ago. The indices were introduced taking into account the experimental fact that geomagnetic variation intensity depends on the observatory location. According to spatial-temporal structure of geomagnetic variations, the following areas can be distinguished: the polar cap, the auroral oval, subauroral latitudes, the middle and low latitudes. Correspondingly, all indices can be divided into 3 groups: I) Indices presenting local geomagnetic disturbances (so-called K indices), which describe the geomagnetic field perturbations at individual observatories and depend on their latitudinal location. II) Indices describing (or meaning to describe) global geomagnetic field perturbations, the foremost being the planetary Kp index derived from the data of subauroral observatories. It is considered that each observatory is located far from any magnetospheric source and at the same time is responsive to any one. III) Indices that should reflect the magnetic disturbance intensity caused by different sources: Dst index should follow the dynamics of the magnetospheric ring current; AE, AU, AL indices should indicate auroral electrojet dynamics; PC-index should describe the electric field over the polar caps (cross-polar cap potential). These indices were induced to quantify the temporal scale of geomagnetic variation amplitudes and became very popular. Though rather rough, they have not changed for ten years and are used by scientists and engineers as real information about the scale and temporal dynamics of geomagnetic activity. Up to now, instead of a concept of *real* geomagnetic activity as total energy of geomagnetic variations generated by magnetospheric and ionospheric current systems in the near Earth's space, a concept of geomagnetic activity as temporal variations of the indices (first of all, of so-called planetary Kp-index) exists. Which incorrect conclusions are caused by using the above-mentioned indices as quantitative rating of geomagnetic activity? First, it is a statistical conclusion on geomagnetic activity dynamics during long time periods. As is known, the annual variation of Kp index in reality exhibits two maxima around equinoctial months. But the cause of these maxima is large index amplitudes during magnetic storms, which number is really maximal in March-April and September-November. During magnetic storms, the auroral zone is extended, and the auroral ionospheric electrojets shift southward to the area of Kp index observatories location. Therefore, the Kp-index observatories become 'auroral observatories' during the main phase of magnetic storms and then they register large amplitudes of geomagnetic variations which are larger than Dst index values. In other words, Kp index describes geomagnetic activity properly only during magnetic storms. But the number of the days when magnetic storms occur is very small compared to the whole number of days in the year (storm geomagnetic activity occurs on not more than 10% of days in the year). The Kp-index describes the geomagnetic activity more or less adequately just in this period.

The real total geomagnetic activity (as the magnetic energy of geomagnetic variations) on other days of the year may be greater than this total value of storm activity, but the Kp index, called planetary index, does not follow it. Correspondingly, the real geomagnetic activity may have quite different annual variation. Second, it is impossible to find a quantitative proportion between geomagnetic activity levels in different intervals of magnetospheric disturbance in a proper way if geomagnetic activity is estimated by the values of geomagnetic indices. We note that the same high-amplitude values of the Dst-index may be observed during different phases of magnetic storm. Under the same solar wind conditions, the magnitudes of geomagnetic disturbances defined by AE and Kp (Ap) indices may be rather different. Therefore, it is impossible to compare correctly the real geomagnetic activity during different phases of the same magnetospheric disturbance based on the Kp, AE, Dst indices only. The geomagnetic activity during different magnetic storms can hardly be compared at all. Third, it is difficult to classify geomagnetic field conditions using geomagnetic activity characterized by the geomagnetic indices. Such a classification is necessary to determine the periods of activity, which are dangerous for spacecraft and ground-based technical systems. At present, the classes of geomagnetic activity are specified by the values of solar wind parameters and Kp, AE, Dst indices. However, the large values of Kp may correspond to a wide range of Dst, and a rather narrow range of Dst (for example, $-150\text{nT} < \text{Dst} < -80$ nT) may correspond to a wide range of Kp (from 4 up to 8). It is possible to overcome the deficiencies of geomagnetic activity quantitative description by using the model estimation of magnetic energy of geomagnetic variations. One can use the model of geomagnetic variations on the Earth's surface such as the IZMEM model [*Feldstein Y.I., Levitin A.E.*,1986] or the models of magnetospheric current systems such as paraboloid model (PM) [http://www.magnetosphere.ru/iso/model/a2000.txt] and Tsyganenko Model [http://nssds.gsfc.nasa.gov/space/model/magnetos/tsyga], which allow us to describe the distribution of magnetic disturbances in the near-Earth space.

2. Quantitative description of the geomagnetic activity derived from the model estimation of the energy of large-scale geomagnetic variations.

In our view, the best estimation of geomagnetic activity in a certain time interval is the estimation of magnetic energy of geomagnetic variations generated by magnetospheric and ionospheric current systems in the magnetospheric volume. If we were able to monitor the spatial-temporal distribution of geomagnetic variations in the near-Earth space and to calculate the magnetic energy of these variations for every hour as $\iiint (H^2/2\mu)dV$, where H is the magnetic field in the elementary volume dV, then the problem of geomagnetic activity monitoring would be solved perfectly. But now we have no such a possibility, and the model descriptions of the external magnetic field in the magnetosphere are rather rough. However, using the up-to-date magnetospheric magnetic field models, such as the PM and Tsyganenko models, yields a good perspective for estimating geomagnetic activity more accurately than from geomagnetic activity indices.

On the other hand, there are approximate models of spatial-temporal distribution of magnetic disturbance vectors on the Earth's surface at high latitudes, parameterized by the solar wind quantities. It is possible on the basis of these models to estimate the value of $E^i_H = (H^i)^2 S_i$. Here S_i is the square size of a spatial cell where the model amplitude of magnetic disturbance horizontal vector H^i is derived. The sum of E^i_H over the whole high latitude region $E_H = \Sigma E^i_H$ would be proportional to the energy of geomagnetic variations and may be a quantitative estimate of geomagnetic activity. One of such models can be the IZMEM model of large-scale geomagnetic variations and ionospheric current systems. The IZMEM model is based on the analysis of regression relations of the form

$$H(\varphi, MLT) = Ky(\varphi, MLT)\times By + Kz(\varphi, MLT)\times Bz + K0(\varphi, MLT),$$

where H(Hx,Hy,Hz) is the vector of magnetic disturbance for every hour of the Local Magnetic Time(MLT) for the corrected magnetic latitude φ, and By, Bz are the components of the IMF vector. From interpolation of the regression equation, the IZMEM model allows us to describe the horizontal vector Hhor (Hx, Hy) of high latitudinal geomagnetic variation parameterized by Bz and By components of the IMF in each cell (which size is 1º in latitude and 15 minutes in longitude). The field inside a cell may be considered uniform. By using the IZMEM model for every UT hour with Bz and By components of the IMF as input parameters, the amplitude of the horizontal vector can be calculated for any latitude $\varphi > 60^\circ$ and for every MLT hour: $(Hhor)^2 = (Hx)^2 + (Hy)^2$. Cell square S_i is calculated as $S_i = [2Re\{Cos(\varphi_1) + Cos(\varphi_2)\}/24x2][Re/180]$, where φ_1 and φ_2 are the latitudes restricting the cell, Re is the Earth's radius. The square of the cells with centers located at the same latitude is the same for all 24 MLT hours.

Geomagnetic activity distribution derived from geomagnetic variations was found for every hour of 1996 - 2003. Annual, monthly, daily, and 3-hour means were also computed to be compared with the geomagnetic activity as given by Ap (Kp)-indices.

In Tables 1-4 the activity values are shown in relative units. The unit was obtained by dividing the activity values by the minimum value of the activity.

2.1. Comparison of the annual variation of geomagnetic activity derived from the energy of geomagnetic variations with Ap-activity (1996 – 2003).

The distribution of the average annual activity for considered 8 years is shown in Table 1. Our calculations suggest that during the period under study, the quietest year was 1996. In Table 1 the activity in 1996 is taken to be 1. The annual activity is presented in relative units. The numbers in brackets ranging from 1 to 8 characterize the relative level of activity. Two right columns show the average annual values of Ap. The Ap index is presented in absolute units (nT) and in relative units. As one can see from Table 1, the quietest year in terms of Ap index is 1997. The geomagnetic activity, as estimated from the magnetic energy of geomagnetic variations, was nearly the same in 2000 - 2003 (the activity in 2003 exceeds that in 2000-2002 only by ~10%), whereas the activity in 2000-2002 in terms of Ap index differs from that in 2003 by ~ 70%. Thus, average annual activity derived from the energy of geomagnetic disturbances over the whole Earth's surface differs from Ap-activity derived from the data of subauroral observatories only.

Table 1

Comparison of geomagnetic activity derived as magnetic energy of geomagnetic variations with Ap index. Numbers in brackets characterize the relative level of activity.

Year	Activity (relative unit)	Annual mean of Ap (nT)	Annual mean of Ap (relative unit)
1996	1.00 (8)	9.3 (7)	1.10 (7)
1997	1.70 (7)	8.4 (8)	1.00 (8)
1998	2.40 (5)	12.0 (6)	1.43 (6)
1999	2.10 (6)	12.5 (5)	1.48 (5)
2000	3.00 (2)	15.1 (2)	1.78 (2)
2001	2.90 (3)	12.9 (4)	1.54 (4)
2002	2.80 (4)	13.1 (3)	1.56 (3)
2003	3.35 (1)	21.9 (1)	2.60 (1)

2.2. Comparison of monthly variation of geomagnetic activity derived from the energy of geomagnetic variations (1996 – 2003)

Table 2 contains monthly average of the activity for every year from 1996 to 2003 and means for all 8 years in relative units (the activity in July 1997 is taken to be 1). The bold number shows the largest monthly mean for every year. One can see from Table 2 that the largest monthly means correspond to October and November, 2003.

Table 2

Monthly variations of geomagnetic activity (in relative units) derived from the energy of geomagnetic variations.

Year	J	F	M	A	M	J	Ju	A	S	O	N	D
1996	1.8	2.4	2.8	2.1	1.8	1.5	2.0	2.0	2.5	3.1	2.1	2.1
1997	3.0	4.5	2.5	3.8	5.1	2.8	1.0	2.5	3.6	5.0	6.5	4.4
1998	3.6	1.7	5.6	3.3	**8.1**	4.0	3.2	**10.7**	6.5	5.6	13.2	**4.6**
1999	4.8	**6.5**	4.8	3.3	2.1	2.4	4.0	5.0	6.0	7.1	5.4	3.0
2000	**5.6**	4.2	2.6	9.2	5.4	4.5	**8.0**	8.7	6.7	12.0	8.1	3.0
2001	3.4	2.6	**14.4**	**11.0**	4.2	2.2	2.1	3.4	3.4	16.5	4.7	4.4
2002	3.1	4.4	3.6	7.8	5.4	2.8	2.6	6.3	**7.5**	15.5	6.3	3.4
2003	3.8	4.6	4.8	3.8	4.4	**5.4**	7.3	9.8	4.6	**18.3**	**16.9**	5.3
Mean	3.6	4.2	5.1	5.5	4.6	3.2	3.8	6.0	5.1	10.4	7.9	3.6

2.3. Seasonal variations of geomagnetic activity derived from the energy of geomagnetic variations (1996-2003).

Seasonal variations of calculated geomagnetic activity are shown in Table 3 in relative units. The activity for July 1997 is equal to 1. The numbers in brackets ranging from 1 to 8 characterize the relative level of activity. The bold numbers show the largest values for each season. According to this table, the maximal seasonal values are related to equinox, except for 1997 and 1998 years.

Table 3

Seasonal variations of geomagnetic activity (in relative units) derived from the energy of geomagnetic variations.

Year	Winter	Equinox	Summer	Mean
1996	2.1 (8)	2.8 (8)	1.8 (8)	2.2 (8)
1997	4.6 (6)	3.8 (7)	3.2 (7)	3.9 (7)
1998	6.6 (2)	5.2 (5-6)	6.5 (3)	6.1 (4)
1999	5.0 (4-5)	5.2 (5-6)	3.4 (6)	4.5 (6)
2000	5.2 (3)	7.1 (4)	**6.8** (1)	**6.4** (3)
2001	5.0 (4-5)	7.6 (3)	6.4 (4)	6.3 (2)
2002	4.2 (7)	**8.6** (1)	4.3 (5)	5.7 (5)
2003	7.0 (1)	8.0 (2)	6.6 (2)	7.2 (1)

2.4. Comparison of 3-hour and daily variations of the geomagnetic activity derived from the energy of geomagnetic variations.

Table 4 presents 20 maximal daily means and 20 maximal 3-hour values of activity in relative units and the dates corresponding to these maximal values. One can also see the daily activity in comparison with the summary Kp-index derived as a sum of eight 3-hour values. Three from the first five maximal values are related to the end of 2003. The difference in the maximal values is factor 4.4, while the summary Kp-index changes 2 times only. Moreover, the dates of maximal Kp are not coincident with the dates of maximal activity. Table 4 shows the dates for 3-hour time intervals as well. As one can see, the first six maximal 3-hour values of activity are related to October and November, 2003, whereas maximal Kp values are scattered within the set of dates.

Table 4

Comparison of geomagnetic activity derived from the magnetic energy of geomagnetic variations with the Kp index based on 20 maximal daily averages and 20 maximal 3-hour values of activity.

Days with maximum ΣKp for 1998 – 2003				3-hour intervals with maximum Kp value for 1998 – 2003			
Date (Y, M, D)	Activity (relative unit)	Σ Kp /ΣKpmin8	ΣKp8	Date(Y, M, D, - number of 3-hour interval)	Activity (relative unit)	Kp /Kpmin	Kp
2003.11.20	4.43	1.6	504	2003.11.20 – 7	4.6	1.4	87
2003.03.31	3.10	2.0	610	2003.11.20 – 8	3.1	1.3	80
2003.10.30	3.04	1.8	560	2003.10.30 – 8	2.5	1.4	90
2003.08.18	2.03	1.7	523	2003.10.30 – 1	2.3	1.4	87
2000.08.12	1.63	1.7	523	2003.10.29 – 8	2.2	1.4	87
2003.10.29	1.80	1.8	585	2003.11.20 – 6	2.1	1.4	87
1998.08.27	1.63	1.8	571	2001.03.31 – 3	3.0	1.4	87
1998.11.13	1.57	1.4	441	2000.04.06 – 8	1.7	1.3	83
2001.03.20	1.49	1.4	444	2001.03.31 – 7	1.6	1.3	83
1998.11.09	1.27	1.5	461	2003.10.29 – 7	1.5	1.4	87
2002.10.01	1.39	1.3	402	2000.08.12 – 4	1.5	1.2	77
1998.09.25	1.38	1.6	480	2001.03.31 – 6	1.4	1.3	80
2001.10.22	1.32	1.6	487	2001.04.11 – 8	1.3	1.3	83
2000.10.05	1.27	1.7	527	2001.04.12 – 1	1.1	1.2	73
1999.10.22	1.24	1.5	460	2000.08.12 – 3	1.1	1.2	77
2002.04.18	1.07	1.3	424	2003.10.30 – 7	1.1	1.4	90
2000.04.07	1.07	1.3	404	2001.03.31 – 4	1.0	1.0	63
2000.04.06	1.05	1.2	376	2001.03.31 – 8	1.0	1.2	73
1998.10.19	1.01	1.3	426	1998.05.04 – 2	1.0	1.4	87
2000.10.29	1.00	1.0	320	2000.04.07 – 1	1.0	1.4	87

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