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Geoeffectiveness of XRA Events Associated with RSP II and/or RSP IV Estimated Using the Artificial Neural Network

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ABSTRACT

A forecasting scheme of geomagnetic activity is presented, based on the analysis of the geoeffectiveness of X-ray flares, accompanied by Type II and/or Type IV radio bursts (RSP) observed on the solar disc in the years 1996 – 2004. The neural network was used to construct this scheme enabling us to determine the probability, with which flares will be followed by a geomagnetic response of a particular intensity. The successfulness of forecasts produced after the fact depended on the flare class and on the combination of radio-burst types. In the case of RSP IV, 58% of the geomagnetic responses of X-ray flares of at least B class were successful. If only RSP II was observed, the forecast was successful only for flares of the X class (67% of successful forecasts). In the second step, a strong geomagnetic response was correctly forecast after geoeffective flares in 58% of the cases. The results are in a good agreement with recent papers based on physical modelling.

Key words: Solar energetic events, solar radio bursts, geomagnetic activity, artificial neural network.

1. INTRODUCTION

The negative consequences of severe geomagnetic disturbances on technical equipment, as well as the negative effects on the health of persons located on board aircraft, require such disturbances to be forecast. The prediction scheme of geomagnetic disturbances can be divided, based on their input data, into schemes based on the knowledge of solar-wind parameters and schemes based on information related to the events taking place on the solar disc.

The first of them (Lundstedt, 1992; Wu and Lundstedt, 1996; Detman, 1998; Boberg et al., 2000; Gleisner and Lundstedt, 2001a, 2001b; Lundstedt et al., 2002a, 2002b; Jankovicova et al., 2002) provide relatively good results with regard to the intensity of the forecast disturbances, nevertheless, since the solar-wind data are obtained at point L1, the warning time is a mere 30 – 60 minutes. This time is too short to take steps to mitigate the negative consequences of such disturbances.

The second of them (Srivastava and Venkatakrishnan, 2002; Srivastava, 2005; Yermolaev et al., 2005; Kim et al., 2005; Berghmans et al., 2005; Robbrecht and Berghmans, 2006; Gleisner and Watermann, 2006a, 2006b) enable the warning time to be extended to 1 – 3 days. The input data of these schemes are usually the information on the existence of a Coronal Mass Ejection (CME), its velocity and place of origin on the solar disc. It has been shown that there is a tendency for the strongest magnetic disturbances to be generated by the fastest CMEs (Kim et al., 2005). However, Gleisner and Waterman (2006a) moreover, proved that enhancements of the ≥ 10 MeV SEP flux, close to the CME onset, can be used to indicate, whether the CME, approaching the Earth, will be followed by a severe geomagnetic disturbance. Ranking the CMEs by velocity and by SEP flux enhancement shows that the latter indicator results in better discrimination between highly geoeffective CMEs and less geoeffective ones.

The forecast scheme we are proposing is based on the analysis of the geoeffectiveness of energetic events observed on the solar disc in the years 1996-2004 (Bochníček et al., 2007). As opposed to the procedures named above, the input information of this scheme is not the CME data, but the data on the X-ray flares accompanied by solar radio bursts (RSP) of Type

II, interpreted as the signature of shock wave initiation in the solar corona, and Type IV, representing upward-moving material in corona (Kosugi & Shibata, 1997). This procedure is justified by the fact that the growing observations support the point that flares and CME are two phenomena in one process just as suggested by Harrison (1996), Dryer (1996), Kosugi & Shibata (1997) and Cliver & Hudson (2002). The analysis (Bochníček et al., 2007) has shown that, if X-ray flares associated with RSP II or/and RSP IV originate from the region bounded by the heliographic coordinates 30ºE-30ºW; 30ºS-30ºN, they have higher probability to reach the Earth and hence, to produce geomagnetic disturbances not only of classes X and M, but even classes C and B. Moreover, the degree of geoeffectiveness of the individual classes of this type of flare can also be estimated. Longitudinal boundaries of the geoeffective region (30ºE-30ºW) are in a good agreement with the results of the paper by Kim et al. (2005) analyzing CME geoeffectiveness and paper by Zhao et al. (2006), analyzing geoeffectiveness of X-ray flares associated with RSP II.

The forecast scheme is based on the method of neural networks and consists of two steps. In the first it is necessary to establish whether the flare will be geoactive, and in the second the degree of its geoeffectiveness (i.e. how severe will its geomagnetic response be).

2. DATA USED

Data on the occurrence of XRA events from daily bulletins issued by the NOAA, Space Environment Center, Boulder, Colorado, USA, for the period 1996 – 2004 were used to construct the model. The model's input parameters are the heliographic coordinates of the location at which the flare occurred, the flare class (B to C, M, X) and information whether the flare was accompanied by a Type II or IV radio burst.

The forecast scheme was tested using the same data in the time interval January 2005 to September 2006.

The problem of assignment of solar energetic events to particular geomagnetic disturbances was discussed in detail in Bochníček et al. (2007). In general, a fixed 30-120 h backward time window was used to look for a candidate for the geomagnetic disturbance. In analyzing complicated situations we drew particularly on the solar wind parameters measured by the ACE satellite at libration point L1.

The geoeffectiveness of the individual events was established according to the intensity of the geomagnetic response, expressed by a sequence of geomagnetic indices.

A disturbance was considered to be severe (s) if the Kp index reached the value 6 at least 3 times in the course of the response.

The disturbance was considered to be of medium intensity (m) if the Kp index reached the value 5 at least 3 times in the course of the response.

The disturbance was considered to be weak (w) if the Kp index, apart from one value of 5, twice reached the value of 4 in the course of the response.

In the remaining cases the responses were considered to be insignificant.

3. METHOD

An artificial neural network was used to construct the model for forecasting the probability with which a geomagnetic response may be expected after a flare, and how severe such response will be.

3.1. The neural network as a nonlinear model

Neural networks represent an independent alternative to nonlinear modelling. A model of a neural network is based on the ability to learn input-output relations and recognize patterns from a database (Hertz et al., 1991; Gurney, 1996). We have used a multilayer perception feed forward neural network, which is represented by:

$g: R^N \rightarrow R^n$.

This consists of one input layer with N inputs, one hidden layer with q units and one output layer with n outputs. The output of the model with a single output neuron (output layer represented by only one neuron, i.e. n = 1) can be expressed according to Nørgaard (1997) by:

$$y = f\left(\sum_{j=1}^{q} W_j f\left(\sum_{l=1}^{N} w_{j,l} x_l + w_{j,0}\right) + W_0\right) ,$$

where W_j is the weight between the j-th neuron in the hidden layer and the output neuron, $w_{j,l}$ is the weight between then l-th input and j-th hidden neuron. We have used the same nonlinear activation function for all the neurons of the hidden layer, as well as for the output neuron in the form of the sigmoid ($f(z) = 1/(1 + \exp(-z))$).

For a given set of M inputs we define the normalized mean square error (NMSE) by

$$NMSE = \sum_{1}^{M} \left(y_s^{out} - y_s^{pred}\right)^2 / M^2 ,$$

where y^{out} denotes the actual given output and y^{pred} the neural network output. The network is trained to minimize the *NMSE* by a gradient method.

3.2. Application of the Artificial Neural Network

In constructing the forecasting scheme, we first sought the relation between the flare characteristic (flare class, RSP type, location on the solar disc) and the probability that the degree of its geoeffectiveness will be at least “w”.

The solar disc was divided into areas 18 degrees in heliographic latitude and longitude, and in each of these the ratio of geoeffective XRAs to the total number of XRAs, which had occurred in that area, was calculated. This ratio yielded the probability with which a flare, originating in the area, would be geoeffective. The procedure is shown in Table 1, drawn up for XRAs of class M associated with RSP II and IV.

Since the analysis proved that XRA events, occurring at high heliographic latitudes, were rarely geoeffective (Bochníček et al., 2007) areas with heliographic latitudes in excess of 45° were assigned zero geomagnetic response probability. The same zero geomagnetic response probability was assigned to areas located in the immediate vicinity of the east and west meridian. The fact that the areas were not of the same size (the areas became smaller towards the pole) was taken into account by presenting the neural networks in the training process with samples, which corresponded to areas with a larger number of observed XRAs. The larger areas were thus assigned larger weights.

Four input quantities and one output quantity were selected as samples to train the artificial neural network. The input quantities were: (1) heliographic latitude and (2) heliographic longitude of the center of the area on the solar disc (real numbers); (3) XRA class (one of three possibilities: B/C, M, X); (4) RSP type (one of three possibilities: II, II & IV, IV). The output quantity was the probability of the XRA event appearing in the given area being geoeffective.

The classical Backward Propagation Algorithm (Gurney, 1996) was used to realize the training numerically. To guarantee the stability of the results, nine neural networks were trained independently, the median of the nine results obtained being considered final.

In view of the limited number of samples (only 93 geoeffective XRAs occurred in the period 1996-2004) the "validation" test was not used to establish the optimum number of neurons. The suitable number of hidden neurons was estimated visually. The criterion therefor was that the boundaries of the "geoeffective" regions on the solar disc should have a reasonably complicated shape. The hidden layer with five neurons satisfied this condition. The architecture of the network used was thus 4 – 5 – 1.

In the next step, the geoeffective XRAs were classified according to the intensity of the geomagnetic response they generated. The samples for the neural network now were four input quantities: (1) heliographic latitude and (2) heliographic longitude of the center of the area on the solar disc (real numbers); (3) XRA class (one of three possibilities: B/C, M, X); (4) RSP type (one of three possibilities: II, II & IV, IV). There was one output quantity, which was the geoeffectiveness of the XRA (possibilities: w, m, s). Five neurons (architecture 4 – 5 – 1) were used in the hidden layer as in the first step. The median of nine independently trained neural networks were again taken to be the result to ensure stability.

4. RESULTS AND DISCUSSION

The first step was to estimate the probability that the geomagnetic response of the XRA would be at least "w" from the position of the XRA on the solar disc and from information about the class of the XRA and type of associated RSP. The XRA was considered to be geoeffective if the probability of its geomagnetic response was at least 50%. All XRAs, observed in the years 1996-2004, were analyzed. This type of forecast is referred to in this paper as "after the fact". In the period 1996-2004, 93 geomagnetic responses, size at least "w", were observed on the Earth's surface. The forecast scheme predicted 40% of the cases of this number (Tab. 2).

The next step was to classify the result by RSP type. It was found that the occurrence of RSP IV significantly improved the successfulness of the forecast, whether in combination with RSP II, or without (Tab. 3). Of the 53 observed geomagnetic field disturbances, 31 were predicted successfully, i.e. 58%.

The forecast improves with increasing XRA class (see Tab. 4). The proposed scheme appears to be very suitable for predicting the existence of geomagnetic responses of X-ray flares of classes B/C, M and X, accompanied by RSP IV, or by a combination of RSP IV & RSP II. A favourable property of the model is also the low number of false alarms.

Figure 1 shows the distribution of geoeffective areas on the solar disc for the separate XRA classes, as well as for the separate types of accompanying RSPs. These geoeffective areas display a moderate asymmetry with respect to the solar equator and central meridian. Whereas the central meridian asymmetry apparently relates to the Sun's rotation, the cause of the equatorial symmetry could stem from the polarity of the solar magnetic field. It should, therefore, be interesting to monitor this phenomenon during the next solar cycle. From a long-term point of view, the parity of the cycle could prove to be an important parameter of the neural network. The distribution of geoeffective areas is in a good agreement with the results published by Kim et al. (2005) and Zhao et al. (2006), who used a large data base of phycs-based, real-time, shock arrival predictions collected in papers by Fry et al. (2003) and KcKenna-Lawlor et al. (2006).

The second step of the forecast scheme was to determine the intensity of the geomagnetic response for the geoeffective flares. Table 5, dimension 3 by 3, compares the observed intensities of the geomagnetic response (on a scale of three: "w", "m" and "s") with those predicted by the model. The drawback of the forecast using this three-stage scale is the excessively high value of some non-diagonal terms. However if the table is reduced to 2 by 2 by combining "w" and "m" (Tab. 6) the diagonal terms become dominant. In other words the model can be used satisfactorily to forecast, whether the expected response will be severe (i.e. "s"). The successfulness of the forecast conceived in this manner is 58% (Tab. 7).

The model was tested using an independent set of data from the years 2005 and 2006 (i.e. data which were not used in producing the model). The results given in Tab. 8 agree well with existing practical experience, obtained in issuing daily forecasts of geomagnetic activity as part of the activity of the Regional Warning Centre Prague.

5. CONCLUDING REMARKS

The results discussed in the conclusion to the preceding section indicate that the proposed model satisfies that which is usually expected of neural networks: i.e. it agrees with existing experience, which it also objectifies and quantifies.

In the first step the output of the model is the probability with which one may expect a geomagnetic response to follow and in the second step an estimate of the intensity of the geomagnetic disturbance. The model does not provide information concerning the time, at which the geomagnetic response is to occur. Estimate of the time arrival can be gained simply in all cases, in which information about the velocity of the transient, associated with the flare, is available. Including the velocity in the neural network directly was originally included in the proposed model, however, due to the lack of data on velocity the results were not convincing, and the velocity was omitted from the model. However, one must keep in mind that the transient can be accelerated or decelerated in the course of its transport. The time and speed aspects have been addressed, physically, by Fry et al. (2003) and McKenna-Lawlor et al. (2006).

According to Gleisner and Waterman (2006a) a certain degree of uncertainty in forecasting the intensity of the geomagnetic response, because the direction and intensity of the field of the magnetic cloud cannot as yet be determined sufficiently in advance, can be compensated to a certain degree by analyzing the flux of solar energetic protons. Within the scope of future research, we shall attempt to integrate this parameter into the forecast model.

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Table 1. Example of the input to the neural network for M-class XRA accompanied by RSP II & IV. The given ratios of geoeffective XRAs to the overall number of XRAs in the separate areas of the 18° by 18° grid on the solar disc were calculated from observations. The ratios are given in per cent. The numbers in the parentheses indicate the number of XRAs from which the ratio was calculated. The zero values of ratios without the number of XRAs are added boundary conditions. Similar tables were created for all combinations of XRA classes and RSP II and/or IV.

Heliograph. longitude	**Heliographic latitude**									
	-81°	**-63°**	**-45°**	**-27°**	**-9°**	**9°**	**27°**	**45°**	**63°**	**81°**
45°	0	0	0	0	0	0	0	0	0	0
27°	0	100 (1)	33 (3)	0 (1)	100 (2)	0 (1)	0 (1)	100 (2)	0 (2)	0 (1)
9°	0	0 (3)	33 (6)	25 (4)	50 (4)	100 (3)	50 (2)	100 (1)	0 (3)	0 (1)
-9°	0	0 (1)	0 (2)	50 (2)	100 (1)	0 (1)	25 (4)	0 (1)	0 (3)	0 (1)
-27°	0 (1)	-	-	0 (2)	25 (4)	67 (3)	-	0 (1)	0 (1)	0 (1)
-45°	0	0	0	0	0	0	0	0	0	0

Table 2. Forecasts of “after-the-fact” geomagnetic responses. All classes of XRA accompanied by RSP II and/or IV, observed in 1996-2004, are considered.

Number of observed geomagnetic responses	Number of predicted geomagnetic responses	Number of false alerts
93	37 (40 %)	14

Table 3. "After-the-fact" forecasts of geomagnetic responses for events from the years 1996-2004, classified by RSP type.

	Number of observed geomag. responses	Number of predicted geomag. responses	Number of false alerts
RSP II	40	6 (15 %)	2
RSP II&IV	41	23 (56 %)	7
RSP IV	12	8 (67 %)	5

Table 4. "After-the-fact" forecasts of geomagnetic activity divided by XRA class and RSP type.

Type of RSP	XRA class	Number of observed responses	Number of predicted responses	Number of false alerts
II	B/C	10	0 (0 %)	0
II	M	21	0 (0 %)	0
II	X	9	6 (67 %)	2
II&IV	B/C	4	0 (0 %)	0
II&IV	M	22	10 (45 %)	5
II&IV	X	15	13 (87 %)	2
IV	B/C	2	1 (50 %)	1
IV	M	7	4 (57 %)	3
IV	X	3	3 (100 %)	1

Table 5. Observed and "after-the-fact" forecast intensities of geomagnetic responses.

	Predicted "w"	Predicted "m"	Predicted "s"
Observed "w"	**5**	10	6
Observed "m"	1	**17**	9
Observed "s"	3	16	**26**

Table 6. Comparison of forecast and observed severe ("s") geomagnetic responses.

	Predicted "w" or "m"	Predicted "s"
Observed "w" or "m"	**33**	15
Observed "s"	19	**26**

Table 7. Successfulness of forecasting severe geomagnetic responses (XRAs accompanied by RSP II and/or RSP IV).

Number of observed geomag. responses "s"	Number of predicted geomag. responses "s"	Number of false alerts (i.e predicted "s" and observed "w" or "m"
45	26 (58 %)	15

Table 8. Example of how the model works for an independent data set from 2005 and 2006. A list of considered solar events is given together with their observed geomagnetic responses, model forecasts of probability of occurrence of a geomagnetic response, and also forecast of the response intensity. The intensity was not calculated if the probability was less than 10% and no geomagnetic response occurred.

Date	Longitude	Latitude	XRA Class	Type of RSP	Intensity of geomag response	Prediction of probability and intensity
09.01.05	-69	-9	M	II	-	0.094
15.01.05	-6	11	M	II&IV	s	0.672 s
15.01.05	8	14	X	II	s	0.769 s
19.01.05	47	19	X	II&IV	s	0.597 s
20.01.05	58	12	X	II&IV	-	0.325 s
14.02.05	-13	-2	B/C	IV	w	0.223 w
19.03.05	48	-8	B/C	II	-	0.01
06.05.05	-28	-9	B/C	II	s	0.138 m
10.05.05	30	-11	M	IV	-	0.165 m
13.05.05	-12	12	M	II&IV	s	0.564 s
14.05.05	90	-10	B/C	II&IV	-	0.026
17.05.05	1	-16	M	II&IV	m	0.539 s
26.05.05	-13	-6	B/C	IV	s	0.18 w
26.05.05	-13	-6	B/C	IV	s	0.18 w
31.05.05	22	12	B/C	II	-	0.085
03.06.05	-21	-18	M	II	-	0.152 m
03.06.05	-9	-17	B/C	II	w	0.122 m
04.06.05	-8	-19	B/C	IV	-	0.11 w
14.06.05	45	8	B/C	IV	m	0.188 s
16.06.05	87	9	M	II&IV	-	0.02
08.07.05	17	12	B/C	IV	w	0.745 w
09.07.05	27	11	M	IV	s	0.718 s
10.07.05	83	-2	B/C	II	-	0.019
12.07.05	64	11	M	IV	-	0.023
14.07.05	73	11	X	IV	m	0.018 s
28.07.05	-84	8	M	II	-	0.096
30.07.05	-61	12	X	II&IV	-	0.091
01.08.05	-30	15	M	IV	-	0.459 w
02.08.05	-47	-12	M	II	-	0.126 m
03.08.05	-36	-11	M	II	-	0.145 m
22.08.05	50	-8	M	II&IV	s	0.104 s
22.08.05	60	-12	M	IV	s	0.034 s
23.08.05	16	70	M	II&IV	w	0.004 s
07.09.05	-89	-6	X	II&IV	-	0.014
08.09.05	-74	-11	X	IV	m	0.04 m
09.09.05	-58	-10	X	II&IV	s	0.03 s
10.09.05	-45	-10	X	II&IV	s	0.059 s
11.09.05	-38	-10	M	IV	s	0.102 m
13.09.05	-11	-13	B/C	IV	-	0.135 w
13.09.05	-4	-10	X	IV	s	0.806 s
14.09.05	-1	-10	B/C	IV	s	0.208 w
02.12.05	-13	-4	M	II	-	0.207 m
05.01.06	57	14	B/C	II	-	0.044
30.04.06	-71	15	B/C	II	-	0.084
01.05.06	2	-11	B/C	II	-	0.096
06.07.06	32	-11	M	II&IV	-	0.345 s
16.08.06	13	-14	B/C	IV	s	0.14 w

Fig. 1. Distribution of areas of geoeffective X-ray flares on the solar disc. (The areas in which the probability of flare geoeffectiveness is higher than 50% are shown in red).