Analysis of lower atmosphere pressure field response for short-time cosmic ray variations by Multifield Comparison Measure method

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Abstract. Pressure variation in lower atmosphere which take place after intensive solar proton events and Forbush-decreases of galactic cosmic rays (GCRs) are analyzed for the period 1980-2006. There were plotted groups of charts (multifields) for 48 solar proton events with energies of particles $E_p > 90$ MeV and for 48 Forbush-decreases of GCRs with amplitudes $dN/N > 2.5\%$. These multifields revealed a growth of matrix norm over North Atlantic region and North of European part of Russia during days following the bursts of solar protons and Forbush-decreases of GCRs, respectively. These results confirm hypothesis about relation of regional cyclogenesis processes with short-term variations of solar and galactic cosmic rays.

1. Introduction
The investigation of solar activity influence on the variations of lower atmosphere parameters now is actual task of Solar-Earth physics. Variations of solar and galactic cosmic rays now are considered as most probable agents of solar activity, which may influence the Earth’s lower atmosphere. Cosmic rays with energies from $\sim 100$ MeV to several GeV can penetrate into the Earth’s atmosphere up to troposphere or lower stratosphere level and also their intensity is strongly modulated by solar activity (for example, [1]).

Veretenenko and Thejll [2-3], Artamonova and Veretenenko [4-5] showed that short-time variations of cosmic rays during solar proton events (SPEs) and Forbush-decreases of galactic cosmic rays (FD of GCRs) may influence the evolution of extratropical baric systems: cyclones and anticyclones, respectively. The physical mechanism of these processes is unclear and now is under consideration. The most probable hypothesis by author’s opinion is one supposed by B. Tinsley (for example, [6]).

Conclusions of these works were based on analysis of atmospheric pressure variation during short-time cosmic ray disturbances using superposition epoch method. It is known that this mathematical method is correct for analysis of a one-dimensional values. In a multidimensional case it requires to use the Pareto sets [7]. As for a two-dimensional atmospheric pressure field, anomalies of one sign can
have various localization and when averaging (superposition of fields) the "indistinct" picture will be received. So, identification of maxima can be made only within some interval of optimality.

In this work we analyze atmospheric pressure variations observed during solar proton events and Forbush-decreases of GCRs using Multifield Comparison Measure method (MCM [8-10]). MCM method allows to receive more objective estimation of connection between several two-dimensional scalar fields (multi-fields) in comparison with superposition epoch method.

2. Multifield Comparison Measure method
The Multifield Comparison Measure method based on analysis of matrix norm calculated for partial gradients of all analyzed fields in every point of manifold.

Let introduce the definition of matrix norm according to [8]. Let $A$ be a $n \times m$ matrix of real numbers. The norm of the matrix $A$ is defined as:

$$\|A\| = \max_{\|x\|_1 = 1} \|Ax\|$$  \hspace{1cm} (1)

where $\|x\|$ represents the Euclidean norm of vector $x \in \mathbb{R}^2$.

Let multi-field $F = \{f_1, f_2, f_3, ... f_m\}$ be a set of $m$ smooth scalar functions defined on a compact two-dimensional manifold $\mathbb{R}^2$. The derivative at point $p(x, y) \in \mathbb{R}^2$ is written as a matrix of partial derivatives:

$$dF(p) = \begin{bmatrix} \frac{df_1}{dx}(p) & \frac{df_1}{dy}(p) \\ \vdots & \vdots \\ \frac{df_m}{dx}(p) & \frac{df_m}{dy}(p) \end{bmatrix}$$  \hspace{1cm} (2)

According to [8-10] *multifield comparison measure* $\eta_p^F$ at point $p$ defined as norm of the matrix $dF(p)$, i.e. $\eta_p^F = \|dF(p)\|$. From the definitions of the multifield comparison measure and the matrix norm, we have:

$$\eta_p^F = \left( \max_{x \in \mathbb{R}^2, \|x\|=1} x^T(dF(p))^T(dF(p))x \right)^{\frac{1}{2}}$$  \hspace{1cm} (3)

where upper index $T$ means transposing.

Let apply the spectral theorem from linear algebra and rewrite matrix product $(dF(p))^T(dF(p))$ as $U^T\Lambda U$, where $U$ is an orthogonal matrix and $\Lambda$ is a diagonal matrix consisting of the eigenvalues of $(dF(p))^T(dF(p))$ as entries in its diagonal:

$$\eta_p^F = \left( \max_{x \in \mathbb{R}^2, \|x\|=1} x^TU^T\Lambda Ux \right)^{\frac{1}{2}}$$  \hspace{1cm} (4)

Since $U$ is orthogonal matrix, i.e. $U^TU = I$, and $x$ is any unit vector, we can rewrite the expression (4) as:

$$\eta_p^F = \left( \max_{x \in \mathbb{R}^2, \|x\|=1} x^T\Lambda x \right)^{\frac{1}{2}} = \max \{\sqrt{\lambda}\},$$  \hspace{1cm} (5)

where $\lambda$ is a diagonal element of matrix $\Lambda$, i.e. eigenvalues of $(dF(p))^T(dF(p))$.

So, to compare the several two-dimensional scalar fields by MCM method [8-10] the next algorithm should be used. Firstly, to compose the multi-field matrix $F = \{f_1, f_2, f_3, ... f_m\}$ with $m$ analyzed scalar fields as arguments, secondly, to calculate the matrix of partial derivatives $dF(p)$ in point $p(x, y)$ for every scalar field $f_i$ and thirdly, to find the maximum norm of obtained matrix. The matrix norm calculated by this algorithm satisfies three important properties: symmetry, coordinate system independence and stability. The proof of these properties is presented in [8]. The results of calculations curried out by MCM method in the MatLab are presented in the next section.
3. Experimental data analysis

In this work we analyzed the atmospheric pressure variations in the Northern hemisphere observed during Forbush-decreases of GCRs and intensive solar proton events. The NCEP/NCAR reanalysis data for the isobaric level 1000 hPa were used. For this investigation 48 Forbush-decreases with amplitude $\delta N/N > 2.5 \%$ for the cold half of the year (October-March) 1980-2006 were chosen based on the Apatity neutron monitor data (geomagnetic latitude 63°N). The list of 48 solar proton events (with energies of particles $E_p > 90$ MeV) for the October-March 1980-1995 was taken from the work [3].

Both for Forbush-decreases, and for solar proton events the maximum of partial derivative matrix norms for two sets of 48 atmospheric pressure fields were calculated on the grid 2.5° x 2.5°. Dates of FDs and SPEs beginnings were considered as zero days. Results of calculations are presented on figure 1 and figure 2: the maximum of partial derivative matrix norms for undisturbed level – on the 9th day before FD and SPE beginnings (a), the maximum of partial derivative matrix norms for days of maximum pressure field deviations, observed in connection with FDs and SPEs – 1st and 4th days after corresponding event onsets (b), maps of difference of matrix norms for disturbed and undisturbed conditions (c).

![Fig. 1](image1)

Fig. 1 Maximum of matrix norm of atmospheric pressure field on the level 1000 hPa in the course of 48 Forbush-decreases of galactic cosmic rays: (a) – undisturbed level, (b) – 4th day after FD beginning, (c) – difference between (b) and (a), white lines shows areas where matrix norm deviations from undisturbed level more than 3σ.

![Fig. 2](image2)

Fig. 2 Maximum of matrix norm of atmospheric pressure field on the level 1000 hPa after 48 solar proton events: (a) - undisturbed level, (b) - 1st day after SPE beginning, (c) - difference between (b) and (a), white lines shows areas, where matrix norm deviations from undisturbed level more than 3σ.
As it is seen from figures 1 (c) and 2 (c), in case of Forbush-decreases partial derivative matrix norm revealed growth over North Atlantic, Scandinavia, North of European part of Russia, North-West Siberia and partly over Arctic Ocean. In case of solar proton events area partial derivative matrix norm growth located only over North Atlantic region. These results are agree with conclusions made in previous works: the intensification of North Atlantic cyclones after solar proton events [2-3] and the blocking anticyclones formation over Scandinavia, Northern Europe and North of European part of Russia in the course of Forbush-decreases [4-5].

So, the results of atmospheric pressure field variation analysis by Multifield Comparison Measure method confirms earlier calculations made using superposition epoch method. Similarity of results obtained by both methods can be explained by the features of the lower atmosphere thermobaric field structure in the Northern hemisphere caused by orography (existence of the centre of atmospheric action in North Atlantic - the Greenland minimum) and the intensification of natural processes of cyclogenesis in the North Atlantic region in the course of short-time variations of cosmic ray intensity.

4. Conclusions

The relations between short-time variations of solar and galactic cosmic rays and pressure in the lower atmosphere on the isobaric level 1000 hPa using Multifield Comparison Measure method were analyzed. It was shown that both Forbush-decreases of GCRs and solar proton events are accompanied with significant growth of partial derivative matrix norms of atmospheric pressure field over the North Atlantic, Northern Europe and North of European part of Russia, this can be explained by intensification of the regional cyclogenesis processes during short-time variations of cosmic rays. The obtained results confirm the conclusions of previous works [2-5] and show that short-time variation of cosmic rays may influence the evolution of extratropical baric systems.

References

[1] Bazilevskaya G A 2005 Adv. Space Res. 35 458
[2] Veretenenko S V, Thejll P 2004 J. Atmos. Sol.–Terr. Phys. 66 393
[3] Veretenenko S V, Thejll P 2005 Adv. Space Res. 35 470
[4] Artamonova I V, Veretenenko S V 2011 J. Atmos. Sol.–Terr. Phys. 73 366
[5] Artamonova I V, Veretenenko S V 2014 Adv. Space Res. 454 291
[6] Tinsley B A 2000 Space Sci. Rev. 94 231
[7] Huettenberger L, Heine C, et al. 2013 Computer Graphics Forum 32 341
[8] Nagaraj S, Natarajan V, Nanjundiah R S A 2011 Computer Graphics Forum 30 1101
[9] Hansen et al (eds) 2014 Scientific visualization (London: Springer-Verlag) p 139
[10] Edelsbrunner H, Harer J, Natarajan V, Pasucci V 2004 Proc. IEEE Conf. Visualization p 275