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Investigation of thunderstorms according to muon hodoscope URAGAN data

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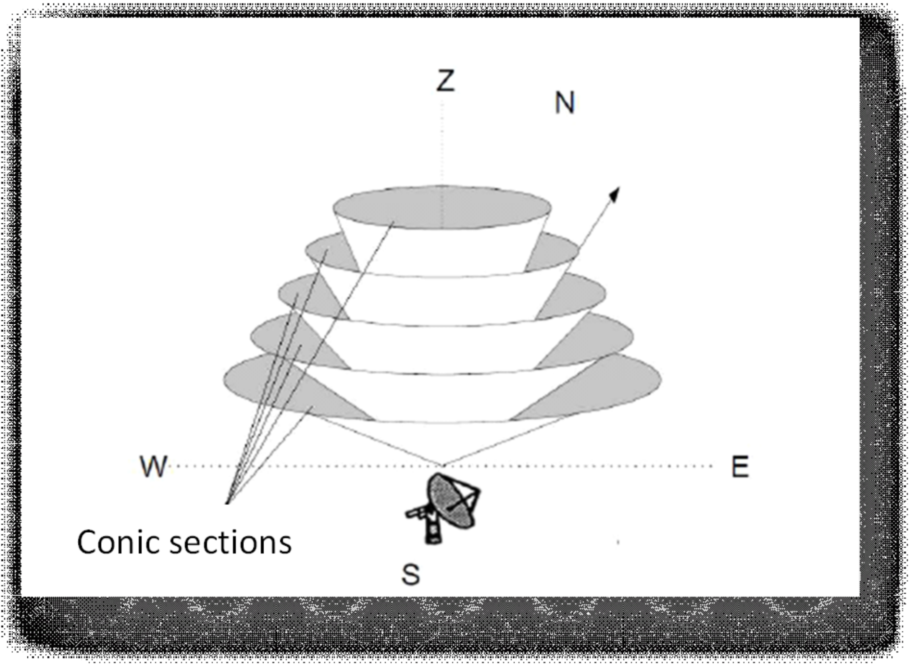
Introduction

Thunderstorms are a clear manifestation of non-stationary processes in the atmosphere and a good material for the development and validation of the main approaches to the study of these processes on the basis of muon flux variations, detected on the Earth's surface.

Identification of thunderstorms and tracking of their development was carried out on the basis of information received with Doppler weather radar DMRL-C (Central Aerological Observatory, Russia).

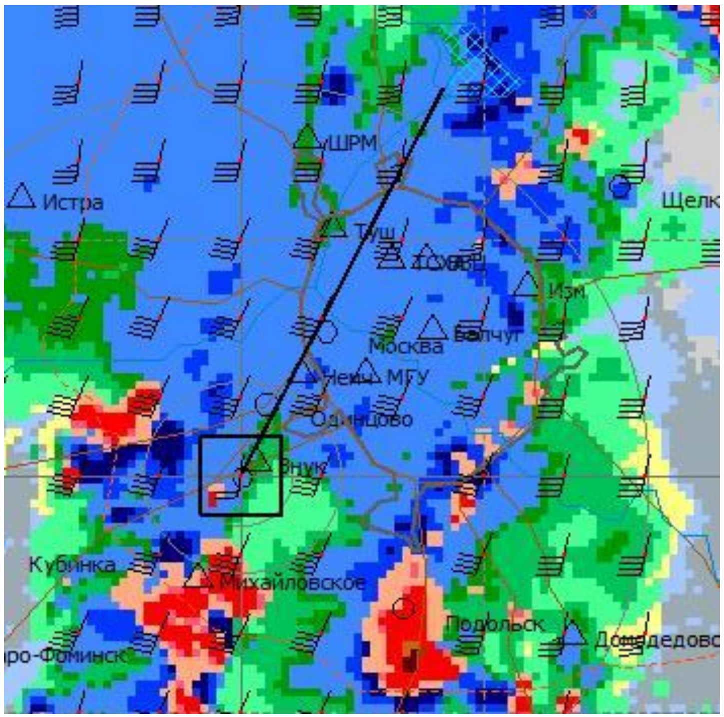
Doppler weather radar DMRL-C



Radio locator determines the radio beam reflectivity from various hydrometeors (droplets, snowflakes, etc.). According to the arrival time and intensity of returned radiation, various meteorological parameters which are then used in the synoptic practice are calculated. Instrumental range of radio beam is 250 km, maximum detection height is 20 km. Zenith angle range is from 0.1° to 86°. Operating frequency range of DMRL-C is from 5.6 to 5.65 GHz. Locator performs cyclical monitoring with a period of 10 minutes in a 24-hour automated mode and provides data with high spatial resolution (0.5 - 1 km) on area of 200 thousand sq. km.

DMRL-C data

Radio locator data represent 3-dimensional maps
of radar scanning (map of phenomena). Resolution of maps is 1×1 km^2.

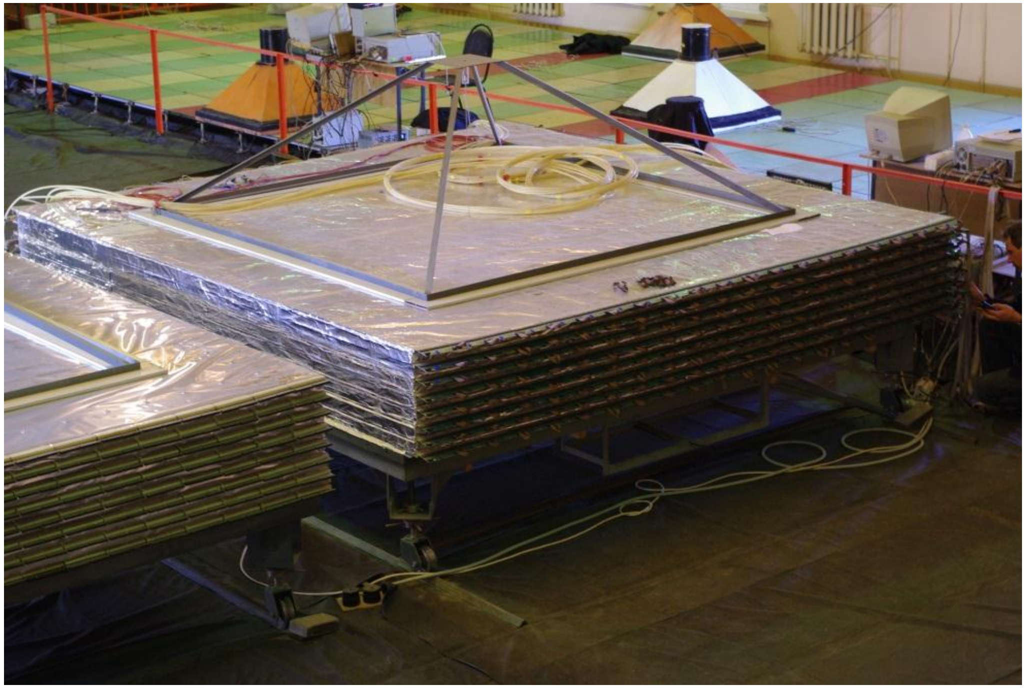


Example of thunderstorm event on July 27, 2015 on the map of meteolocator. Black square represents the locator position, inclined vertical line points the direction of air mass movement.

Allows to determine the type of atmospheric phenomena, type of cloudiness, speed and direction of meteorological formation movement, boundaries of clouds, precipitation, turbulence and convective atmospheric formations, etc.

Muon hodoscope URAGAN

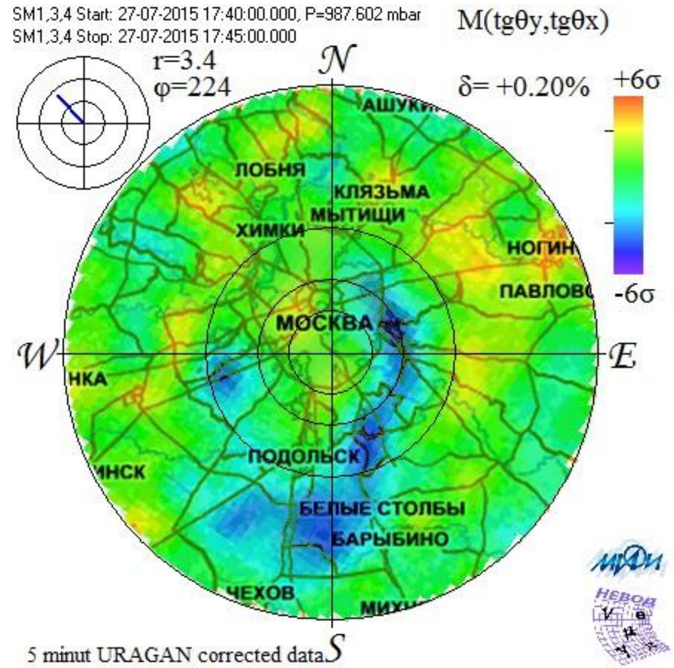
URAGAN (55.7°N, 37.7°E, 173 m above sea level) is the coordinate detector that allows to investigate variations of the muon flux angular distribution on the Earth's surface.



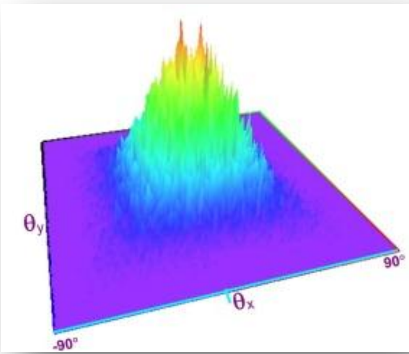
URAGAN consists of four independent supermodules (SM), total area ~ 46 m^2. Each SM is assembled of 8 layers of gas-discharge chambers (streamer tubes) equipped with two-coordinate system of external readout strips which provides a high spatial and angular accuracy of muon track detection (correspondingly, 1 cm and 1°) in a wide range of zenith (0°-80°) and azimuthal (0°-360°) angles in the real time mode.

URAGAN data

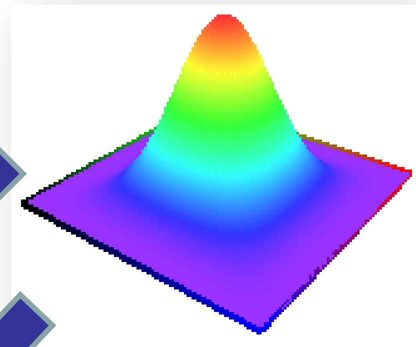
Every minute, angular distribution of muons is recorded in a 2-dimensional angular matrix, which represents a muonograph of the upper hemisphere with one-minute exposure.



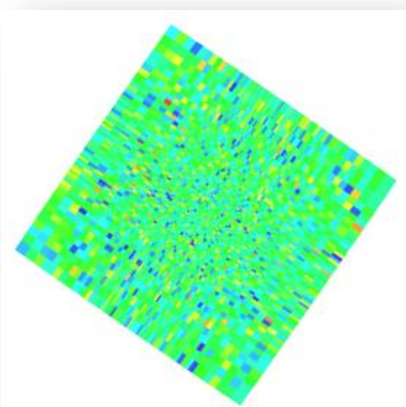
Matrix with dimensions of 90 × 90 cells



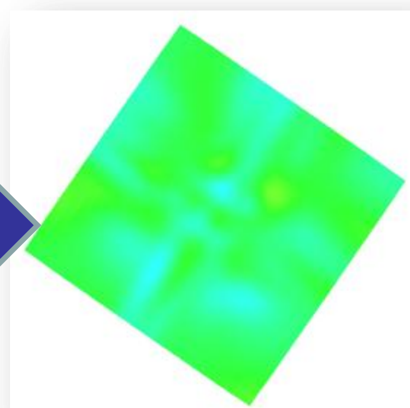
Averaging



Gaussian filter



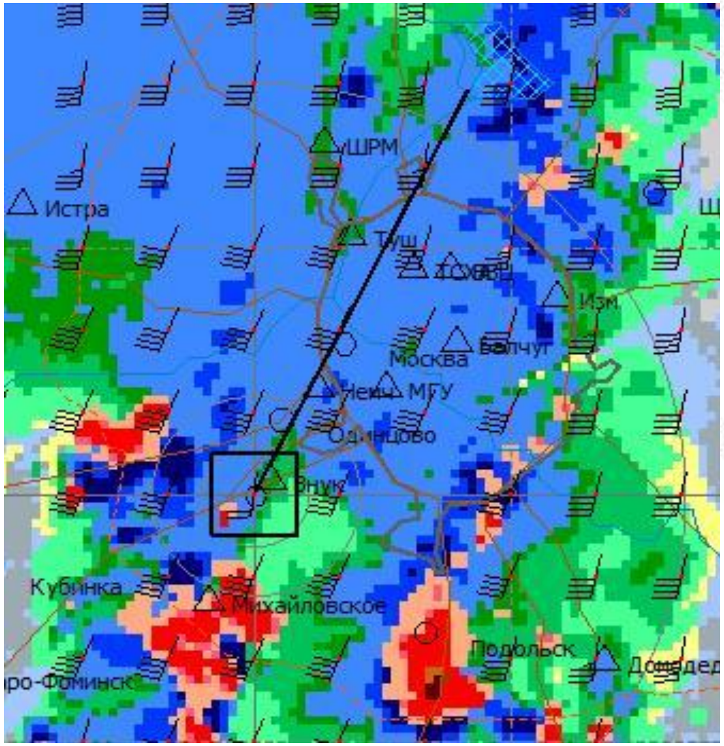
Normalization

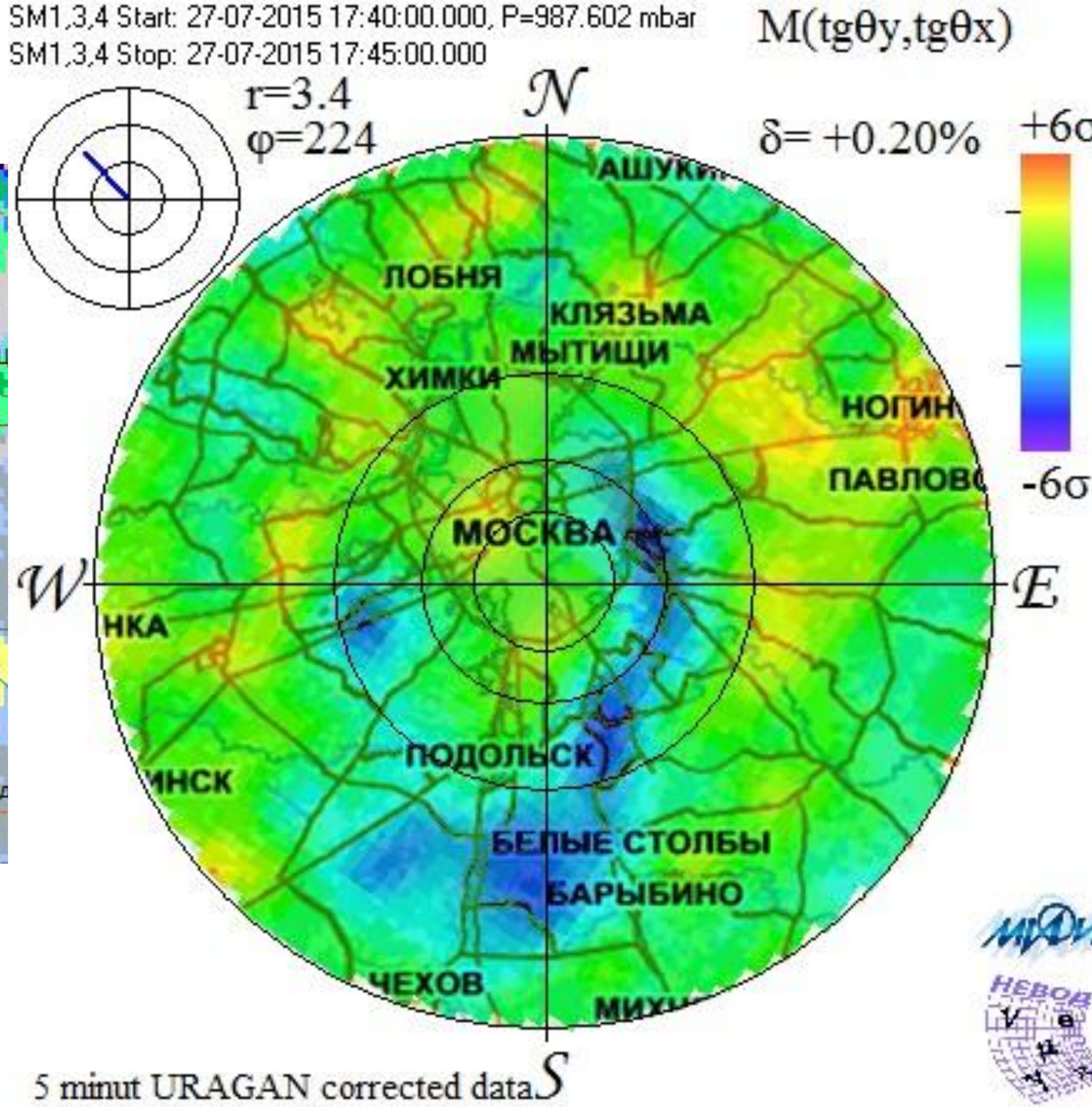


Muonographs are matched according to the average height of muon production (~ 16 km). The crosshair in the center of the image shows the setup position. The scale in the upper right corner of the image shows the deviation of the intensity of the muon flux arriving from different directions from the average daily value in units of standard deviations.

In the upper left corner, the absolute value and direction of the relative anisotropy vector $\vec{r}$ and the relative intensity δ (%) are shown.

Comparison Doppler maps and muonographies

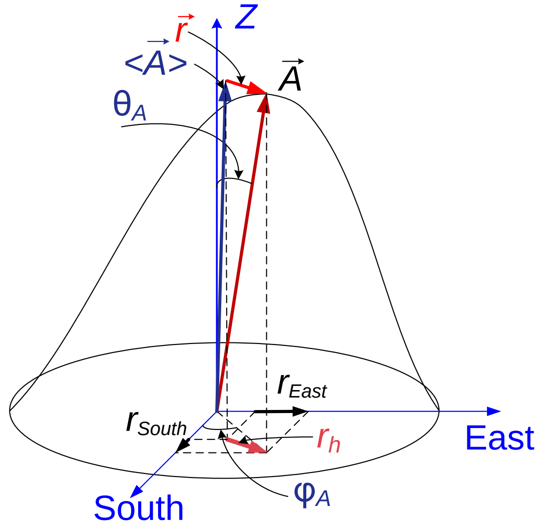




This example shows that the area of thunderstorm corresponds to minimum muon flux.

Local anisotropy vector

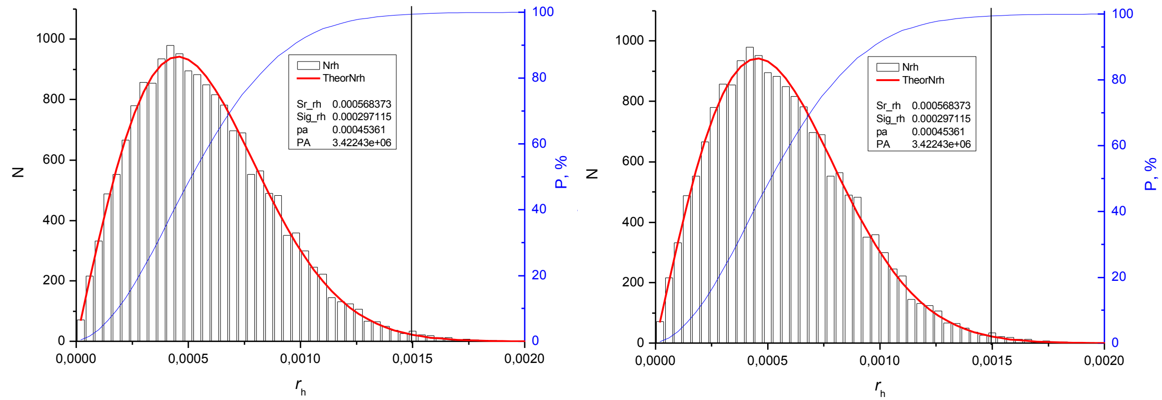
For a quantitative estimation of changes, the local anisotropy vector is used.



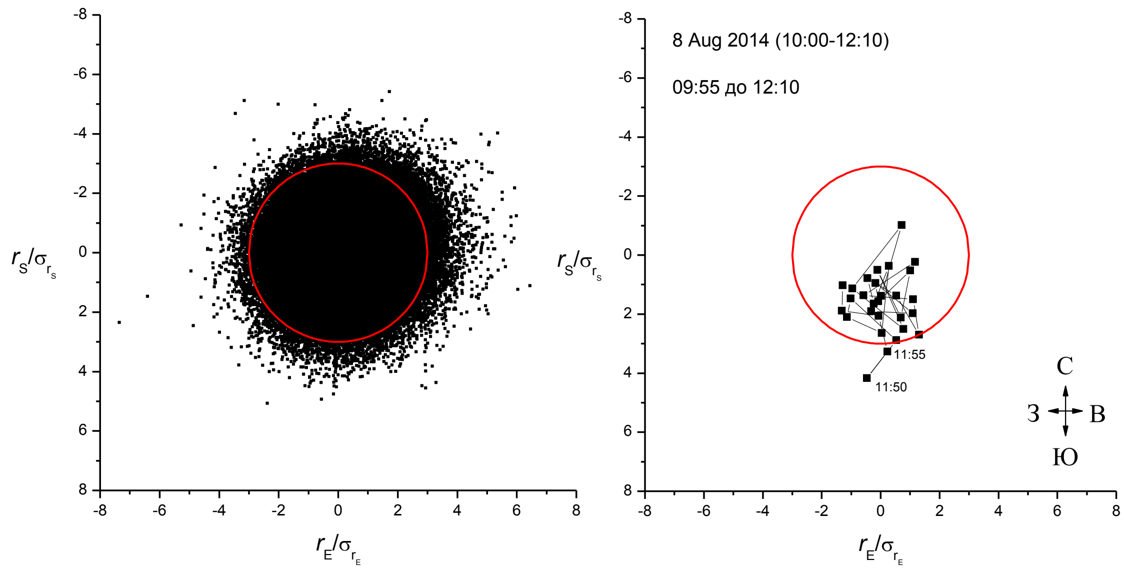
For the study of 2-dimensional variations of muon flux registered by the URAGAN, a local anisotropy vector ***A*** is used.
Local anisotropy vector indicates the average arrival direction of muons, which is close to the vertical.
To study its deviations from the mean value, the relative anisotropy vector ***r*** and its horizontal projection r_h are used:

$$\vec{r} = \vec{A} - \langle \vec{A} \rangle \qquad r_h = \sqrt{r_E^2 + r_S^2}$$

Differential and integral distributions of values of the muon flux relative anisotropy parameters



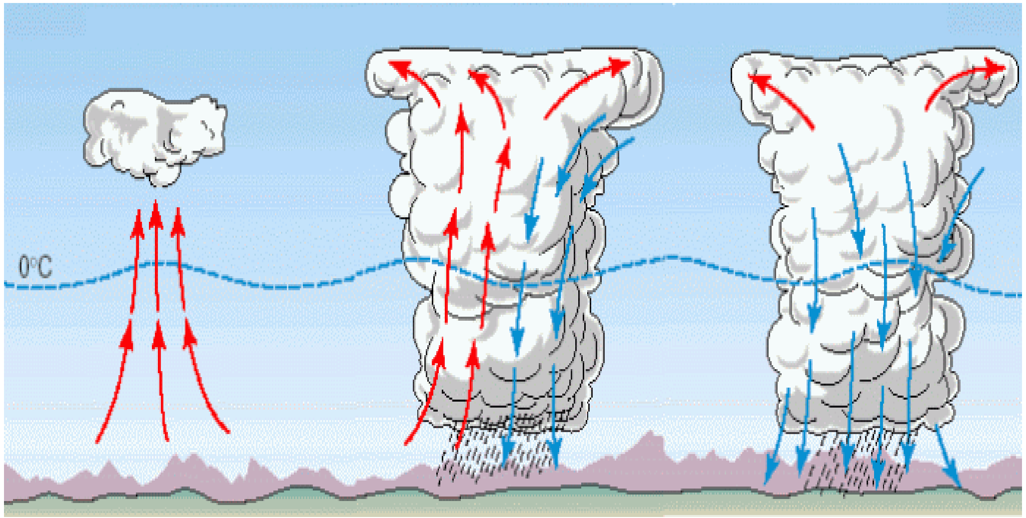
Correlation between projections r_E and r_S during the period from 2014 to 2015



Thus, from the integral distributions calculated for the above mentioned quantities, it follows that at magnitudes of 3σ, the probability of accidental deviation is less than 1%.

Analyzed thunderstorm phenomena (TPh)

Thunderstorm is a complex phenomenon of formation and development of cumulo-nimbus cloud which is accompanied by multiple electric discharges (lightning) and sound effects (thunder).



During the period from 2014 to 2015, 71 TPh have been detected according to the data of DMRL-C over the Moscow region. 24 of them were excluded because they coincided with the IMF and EMF disturbances, **47 thunderstorms** have been selected for the further analysis.

Duration	%	By the time of day	%
0.5 – 2 h	77	06h -14h	53
2 - 3 h	13	14h - 22h	19
3 - 5 h	10	22h - 06h	16

Distribution of thunderstorm phenomena on atmospheric fronts and types of thunderstorm cells

Front\Type of thunderstorms	One cell	Multicellular
Warm	9	4
Cold	14	4
Occluded	11	0
Mixed	2	0
Front absence	3	0
TOTAL	**39**	**8**

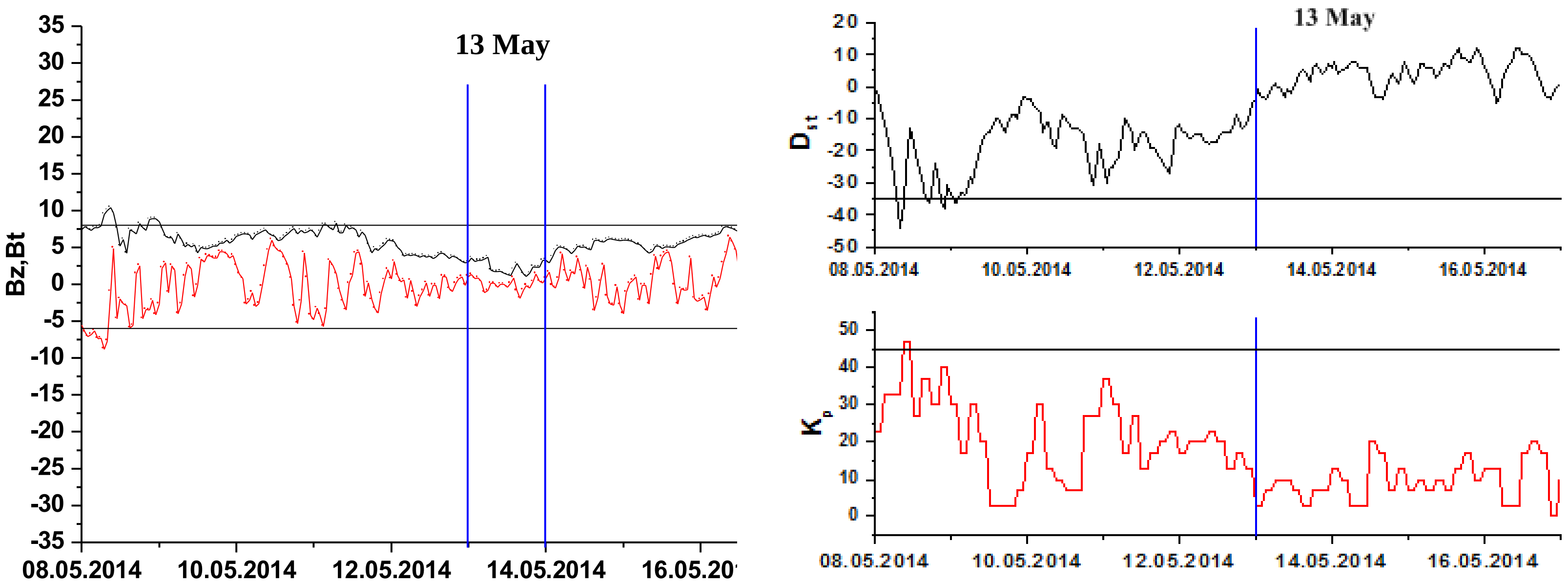
Stages of thunderstorm analysis

Analysis of storm phenomena according to URAGAN and DMRL-C data includes several basic steps:

1. Analysis of the situation in the heliosphere and magnetosphere.
2. Study of the meteorological situation.
3. Visual comparison of meteorological maps and muonographies.
4. Studying of muon flux integral characteristics.
5. Studying of temporal characteristics of muon flux relative anisotropy.
6. Studying of muon flux azimuthal distributions, including in geographical directions.

Situation in heliosphere

In the context of thunderstorm on May 13, 2014

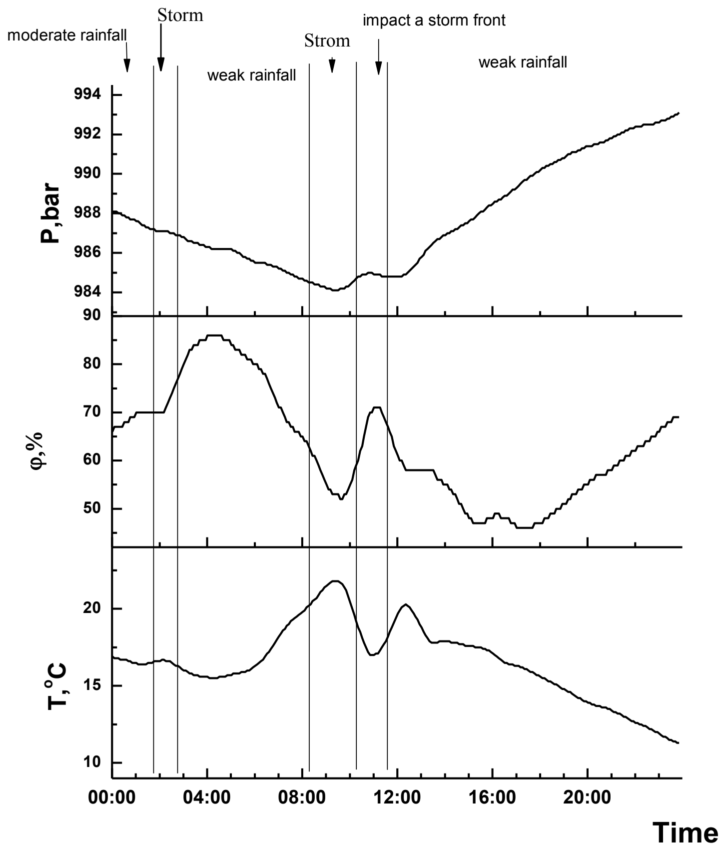


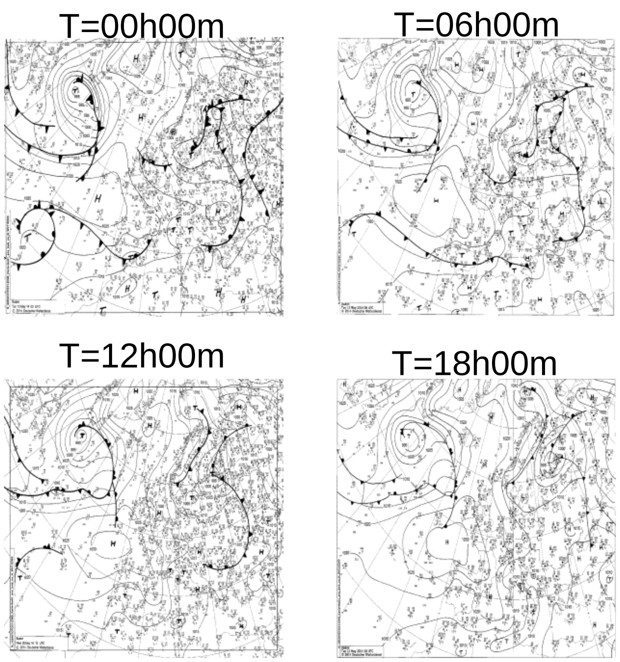
Variations of IMF parameters (left): black curve – magnitude of B, red curve – Bz. Condition of EMF: Dst (upper right) and Кp (bottom right) during the period May 8-17, 2014.

As can be seen from figures, on May 13, 2014 the geomagnetic situation was quiet.

Meteorological situation

In the context of thunderstorm on May 13, 2014



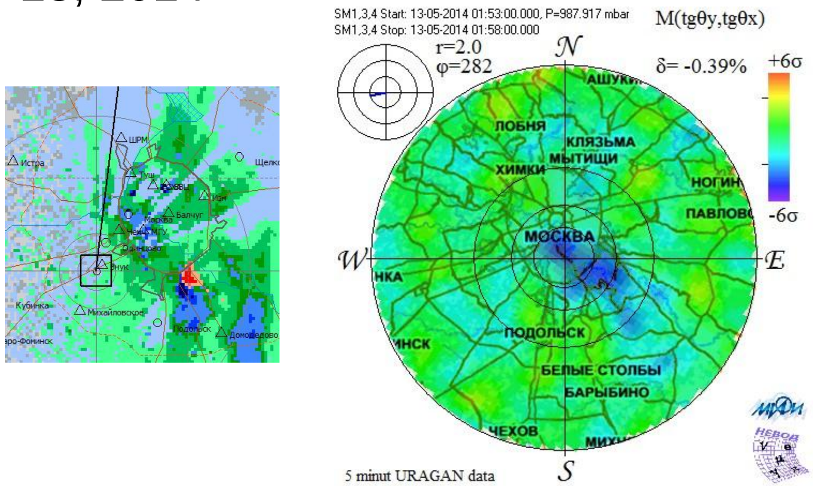


Time (UTC), (DMRL-C)	Duration	Magnetosphere			Weather	
		Kp	Dst	Bz,Bt	precipitation	air mass speed, m/s
01:53 – 02:43	00 h 50m	13	-1	1, 3.6	moderate rain	17-19
08:43 – 10:13	01 h 30m				rain	17-20
10:22 – 11:33	01 h 11m				weak rainfall, cloudiness	18-20

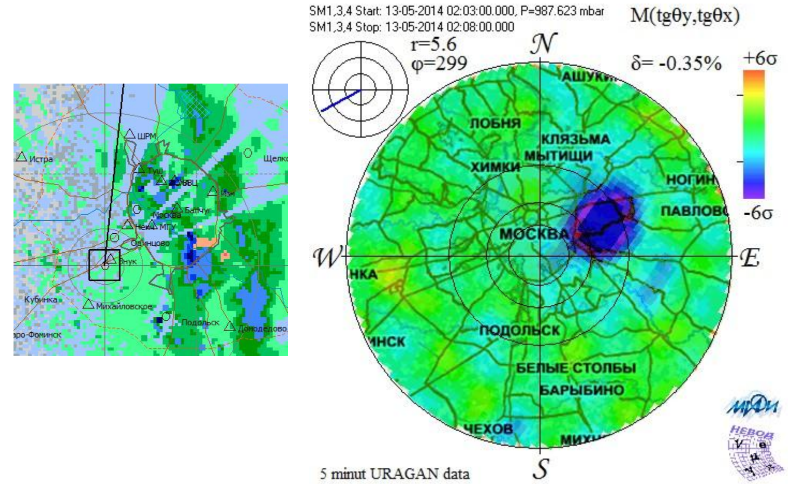
Visual comparison of maps and muonographies

May 13, 2014

01:52



02:02



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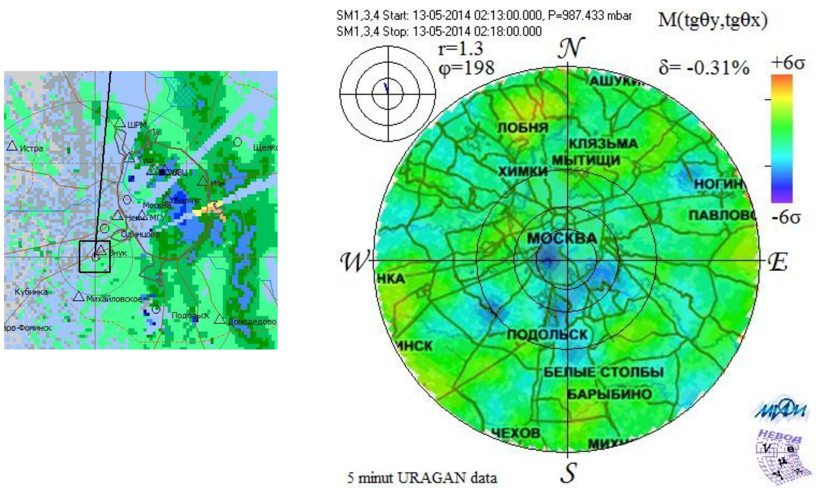

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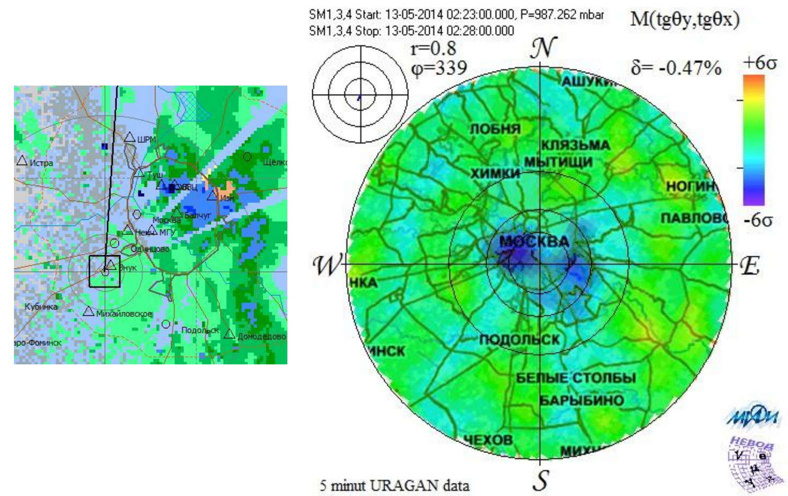
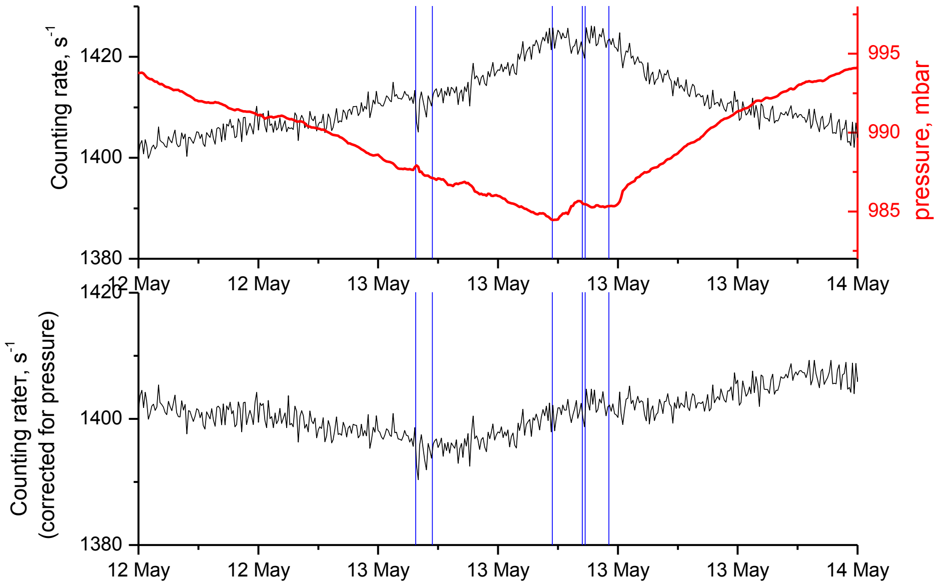
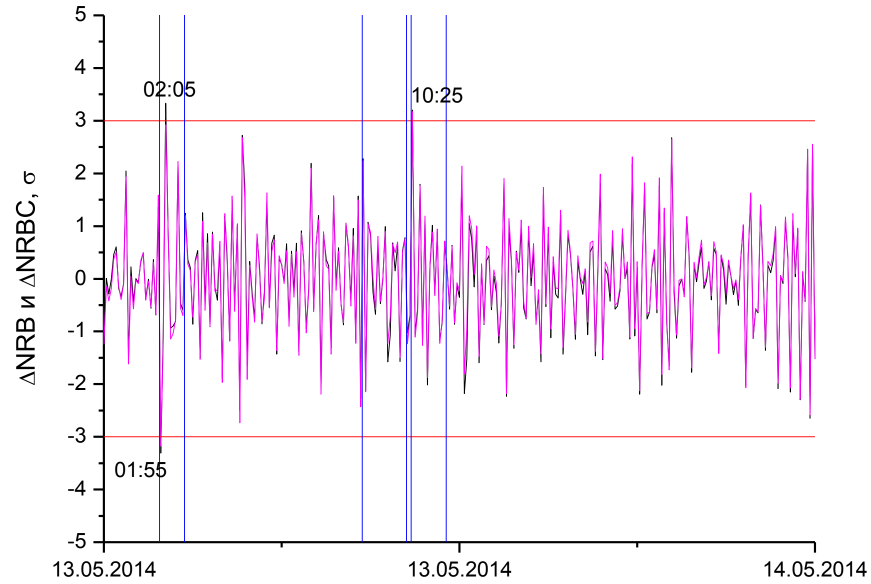


These pictures illustrate the changes of results observations by two set-ups.

Studying of the muon flux integral characteristics

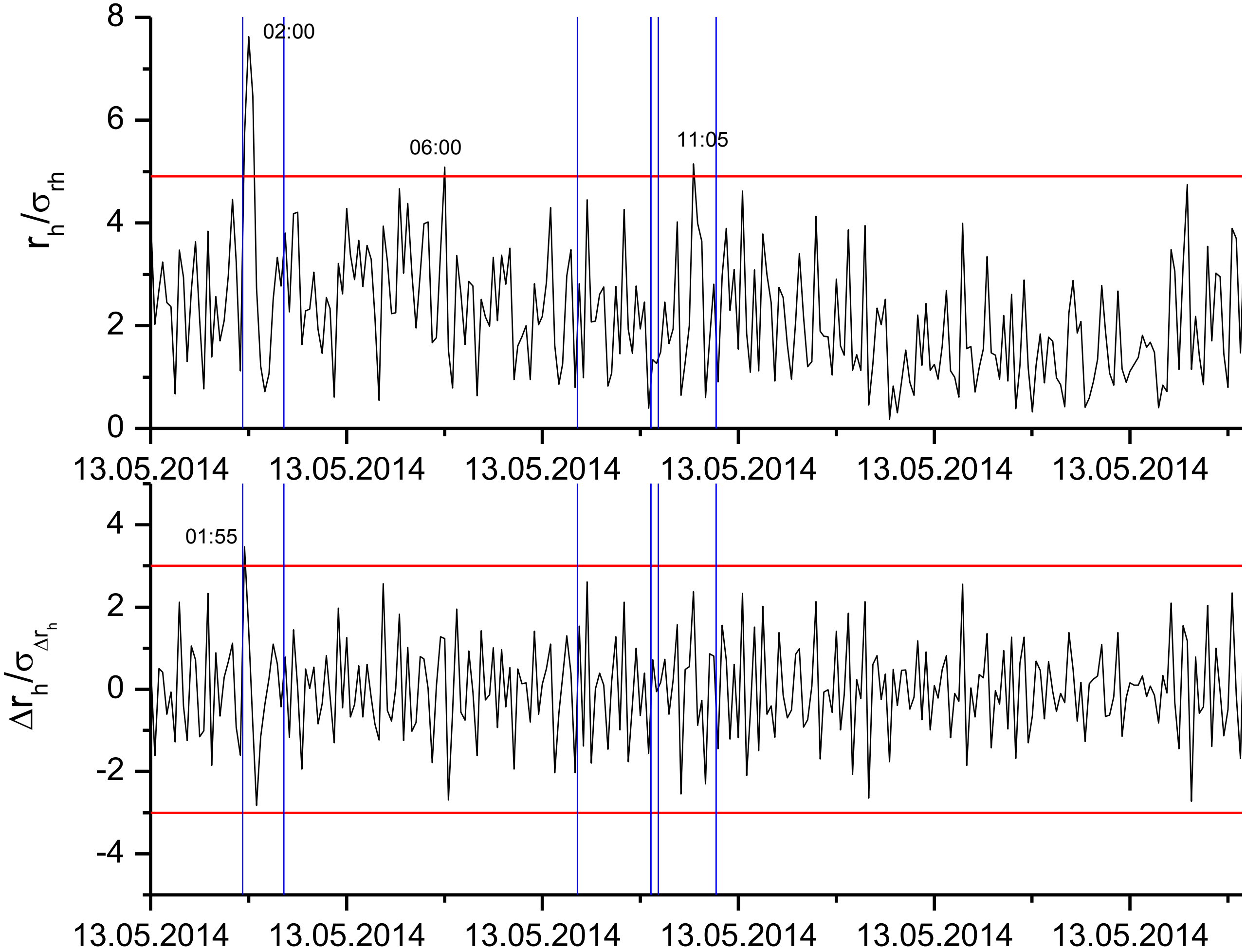




Blue vertical lines show time intervals for thunderstorm events.
The anti-correlation between counting rate and atmospheric pressure is clearly seen.
The "thunderstorm peak " causing by the variations of the muon flux can be noticed.

The counting rate variations corrected for pressure A_{Nrbc} (in %) were calculated. These data were used to analyze the time when the variations of counting rate exceeded 3σ.

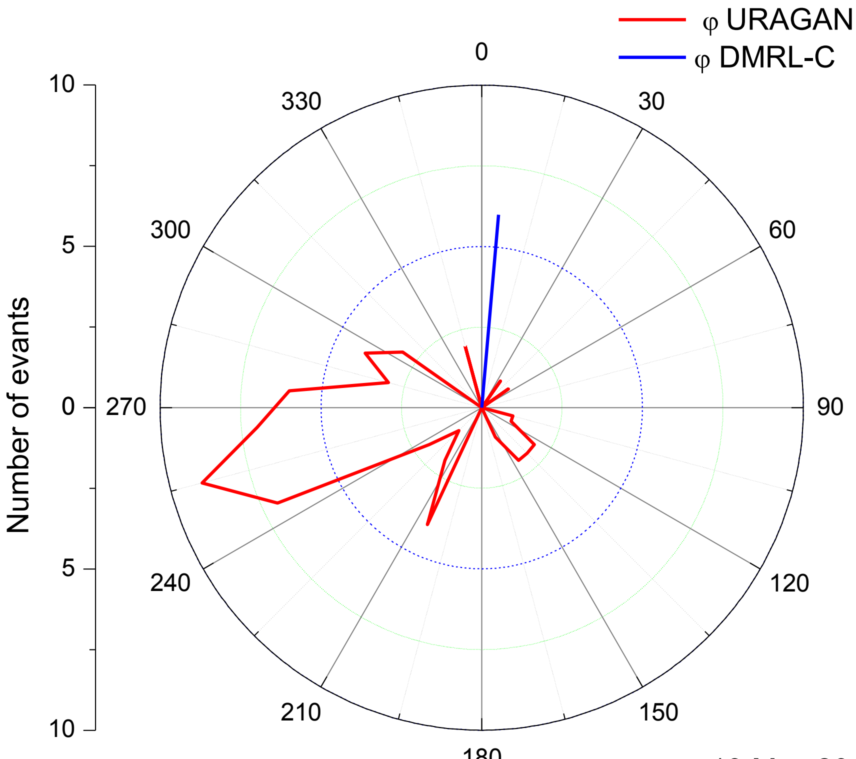
Temporal variations of parameters of the muon flux local anisotropy

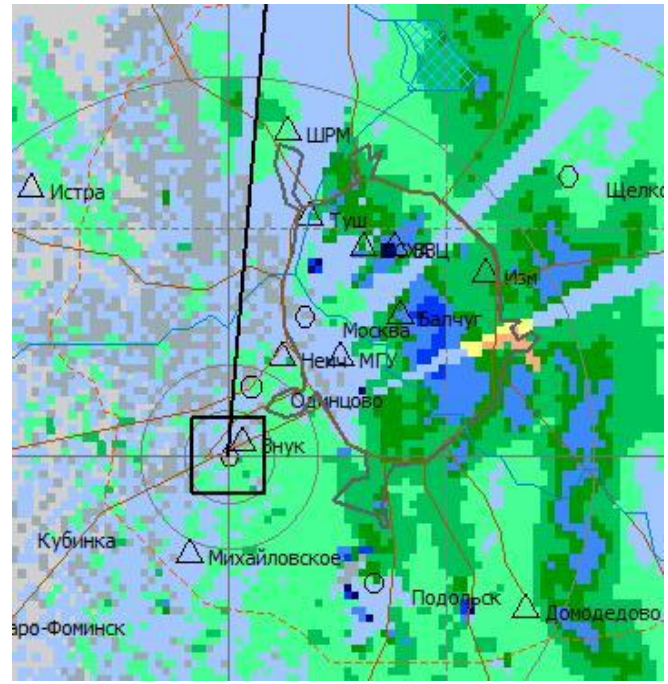


Upper picture for horizontal projection of local anisotropy vector.
Lower - for change of this parameter for an hour.
As can be seen from the graphs, not for all thunderstorms anisotropy of the muon flux is observed.

Spatial variations of parameters of the muon flux local anisotropy

Frequency distribution of azimuthal directions of air mass movement (blue line) and of muon flux anisotropy variation (red line).

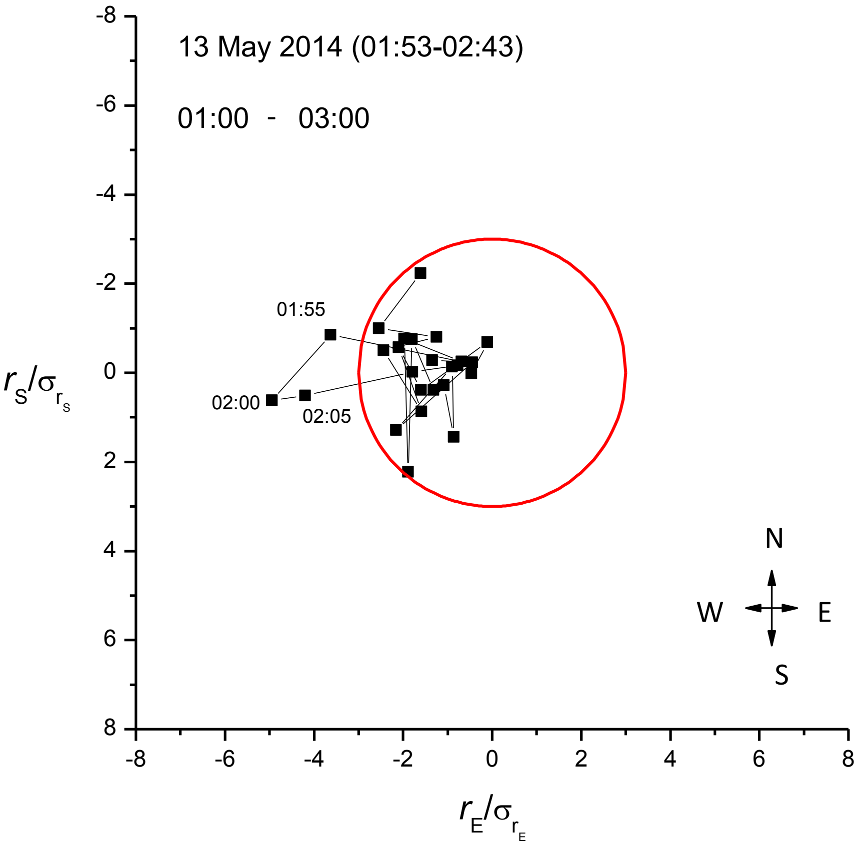




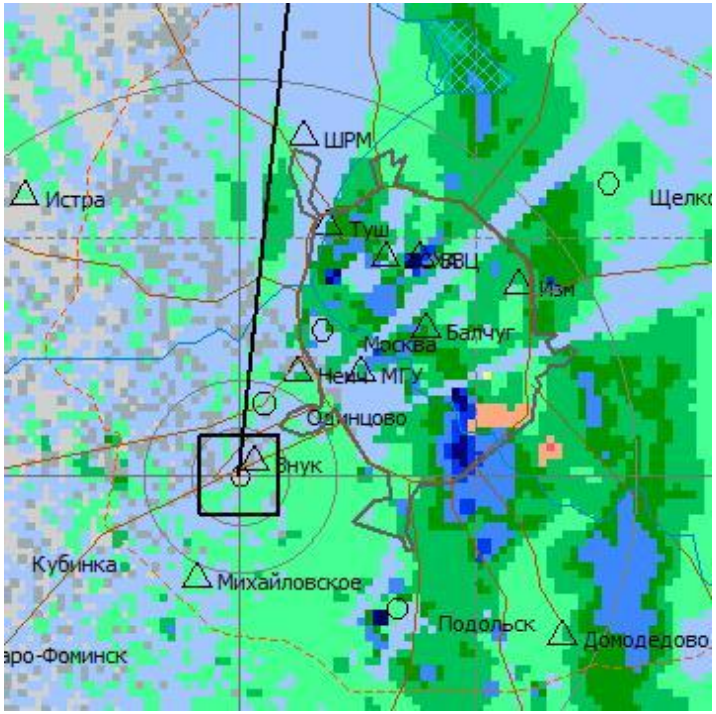
13 May 2014 (01:50-02:50)

Maximum of the muon flux was observed from the West (minimum – from the East, correspondingly). It is in a good correlation with the passage of thunderstorm front and clouds with high water content from the North to the East of the MH URAGAN location.

Comparison of TPh development dynamics according to the DMRL-C and correlation dependence between r_S and r_E *parameters*



02:02



The use of these correlations allows to observe changes of the anisotropy in the muon flux every 10 minutes. The value of r_S and r_E exceeding 3σ are observed in the direction of the muon flux maximum. Correspondingly, the minimum was at the opposite side where the increase of the atmospheric density (water) was observed.

Variation of muon flux characteristics at different meteorological parameters of thunderstorm phenomena

Efficiency of thunderstorm phenomena registration of the MH URAGAN

MH parameters	Thunderstorm type		Front					47 events
	1-cell	Multicell	Warm	Cold	Occluded	Mixed	Absent	
r_h	69%	63%	**85%**	**78%**	45%	50%	33%	**68%**
r_s/r_e	67%	75%	**85%**	**83%**	45%	50%	33%	**70%**
Δr_n	33%	50%	54%	44%	18%	0%	0%	36%
A_{nrb}	46%	75%	69%	50%	45%	0%	33%	51%
N_{rbc}	31%	25%	54%	28%	9%	0%	33%	30%
N_{rb47}	28%	38%	31%	33%	9%	0%	33%	30%

Bold font shows the maximum values of characteristics with a high degree of consistency (> 80%).

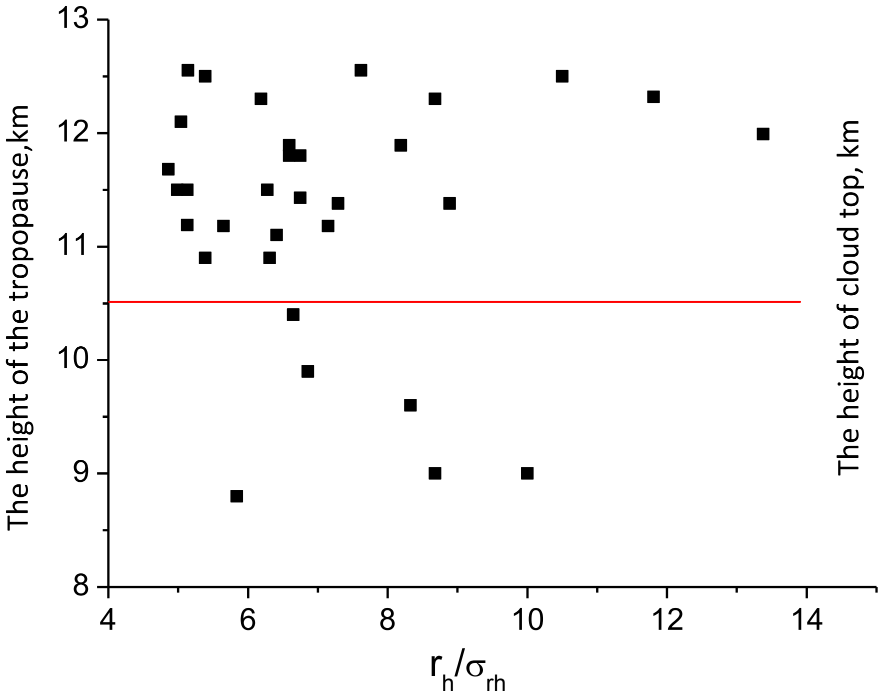
The parameters of the muon flux anisotropy (r_h,r_S/r_E), which generally allow identification of TPh with an efficiency of about 70% are more sensitive to atmospheric disturbances. If TPh is accompanied by warm and cold fronts, its identification efficiency is more than 80%.

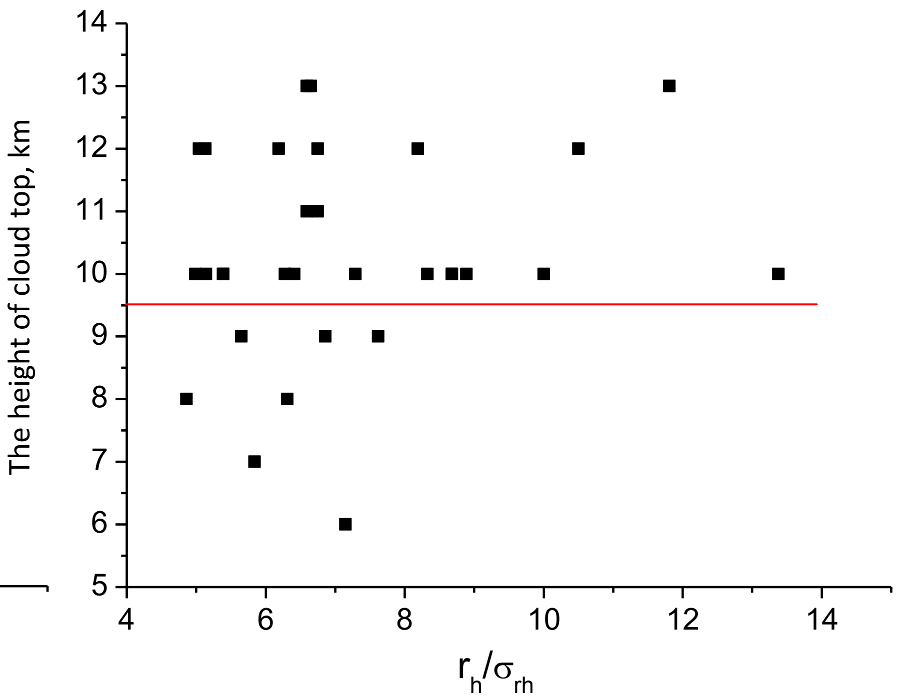
MH parameters	Perceptions	TPh passage			Rate of air mass passage		
	shower	over MH	through MH	Surroundings	High	Average	Low
r_h	74%	73%	**85%**	67%	**75%**	67%	64%
r_s/r_e	77%	77%	46%	70%	**75%**	67%	68%
Δr_n	41%	42%	**85%**	35%	38%	33%	36%
A_{nrb}	59%	69%	69%	50%	31%	67%	61%
N_{rbc}	31%	35%	31%	28%	25%	67%	29%
N_{rb47}	33%	31%	46%	30%	31%	67%	25%

During the passage of TPh through the MH URAGAN, it can be identified using not only r_h but also the rate of its variation (Δr_h) which efficiency is about 85%.

Using the anisotropy parameters (r_h, r_S/r_E), the TPh passing in the surroundings of MH can be identified with the efficiency of 70%.

Correlation analysis of muon flux characteristics and meteorological parameters of thunderstorm phenomena





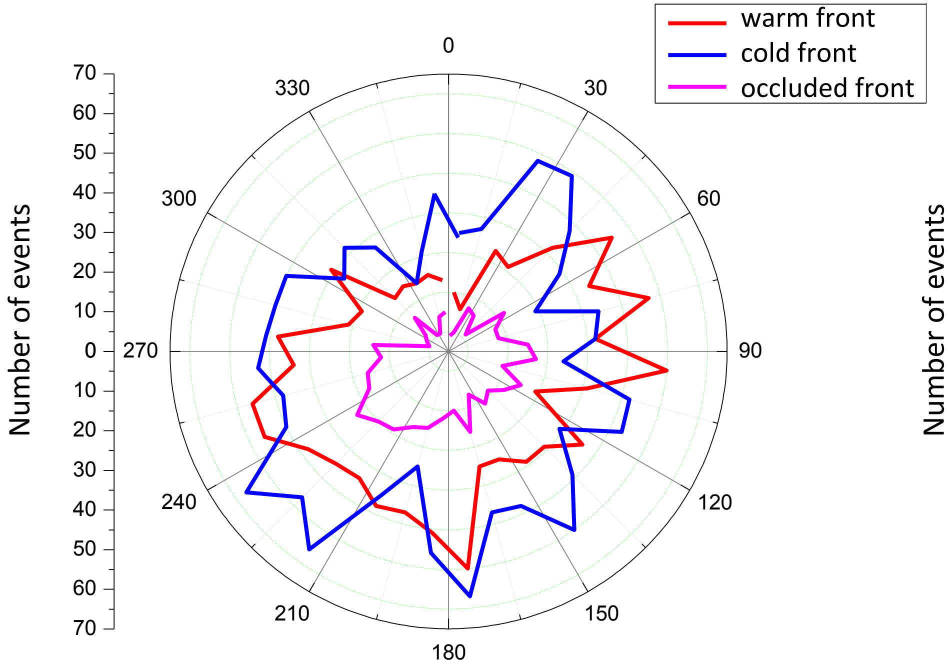
Muon flux parameters	Height of the tropopause, km		Height of cloud top, km	
	≤10	>10	≤9	>9
r_h	50%	**73%**	50%	**76%**
r_s/r_e	50%	**76%**	50%	**79%**
Δr_n	50%	32%	29%	39%
A_{nrb}	50%	51%	50%	52%
N_{rbc}	30%	30%	29%	30%
N_{rb47}	30%	30%	29%	30%

Results of the analysis of the dependence of r_h on the height of tropopause and cloud top shows that, mainly, the muon flux anisotropy is observed at H_{tropo} > 10,5 km and at $H_{Cloud\ Top}$ > 9.5 km. It is in a good agreement with the altitude of the muon flux generation in the atmosphere (10-20 km).

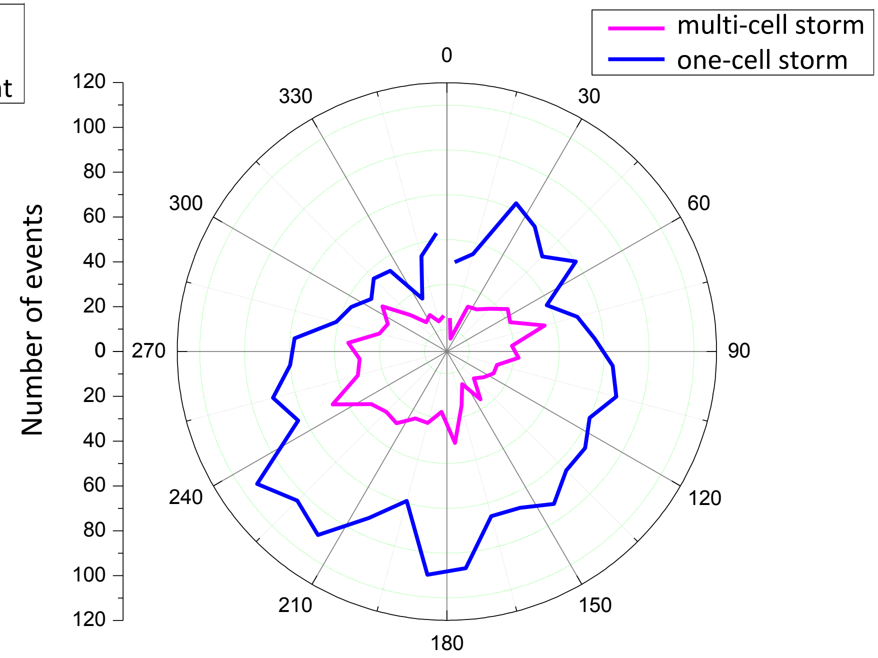
Spatial characteristics of thunderstorm phenomena for various types of fronts

Distribution of 47 TPh on azimuthal directions of horizontal projection of the vector of muon flux relative anisotropy and air mass movement

For the front types



For the thunderstorm types

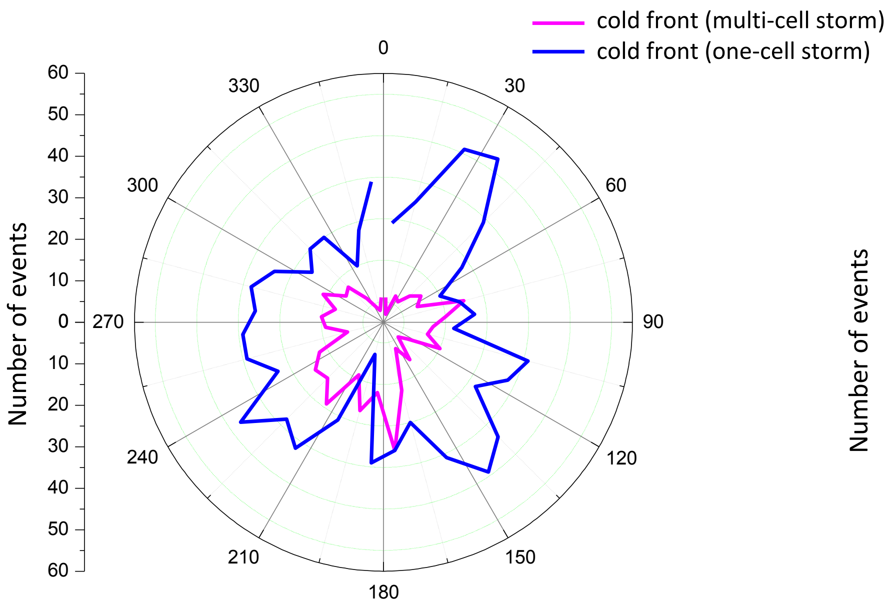


Differences in the distributions for warm and cold fronts and for 1-cell and multi-cell thunderstorms are not seen.

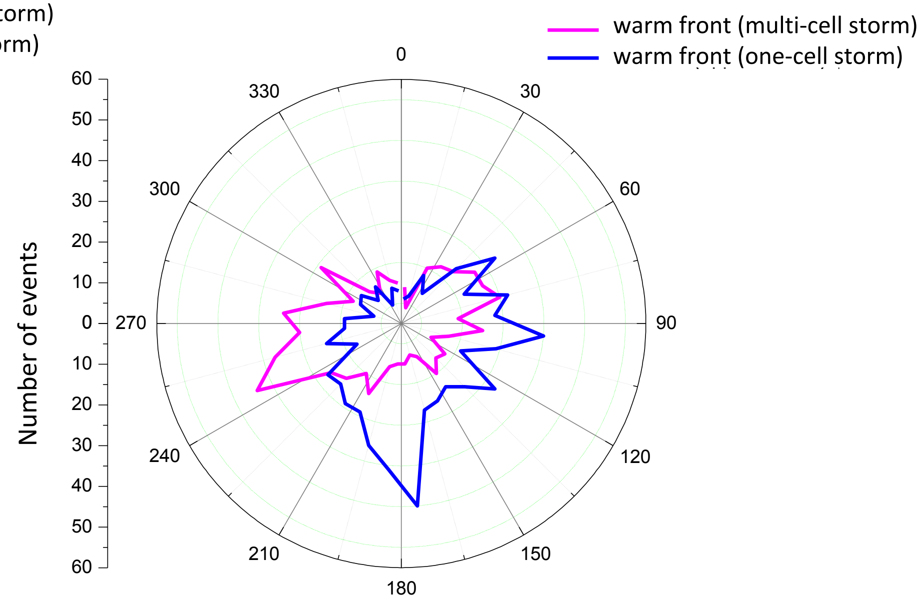
Spatial characteristics of thunderstorm phenomena for various types of fronts and thunderstorms

Distribution of 47 TPh on azimuthal directions of horizontal projection of the vector of muon flux relative anisotropy and air mass movement

Cold front



Warm front



Differences in the distributions for various types of thunderstorms during the passage of warm and cold fronts have been revealed: during the **cold fronts** the maximum of **1-cell thunderstorms** corresponds to angles of **0°–45°** and maximum of **multi-cell thunderstorms** is from the opposite directions (**165–240°**); during the **warm fronts** the maximum of **1-cell thunderstorms** is in range of **150–210°** and of **multi-cell thunderstorms – 210°–270°**.

CONCLUSION

1. The methods of thunderstorm phenomena analysis according to the data of the DMRL-C and MH URAGAN have been developed. These methods allow to compare the maps of radio locator scanning and the muonographies.

2. The analysis of thunderstorm phenomena according to the data of DMRL-C and MH URAGAN has shown:

- for the quantitative description of maps and muonographies the best are: the correlations between the projections of the muon flux relative anisotropy vector to the directions North-South and East-West and the azimuthal distribution of direction of the relative anisotropy vector;
- the muon flux anisotropy parameters (r_h, Δr_h и r_S/r_E) are the most sensitive to atmospheric disturbances and allows TPh identification with efficiency of 70% in general and with efficiency of about 85% if the TPh passes through the MH URAGAN;
- the differences in distributions for various types of thunderstorms at the passage of warm and cold fronts has been revealed;
- the muon flux anisotropy is mainly observed at altitudes of tropopause > 10.5 km and at altitudes of the upper limit of the clouds > 9.5 km which are close to the altitudes of muon generation in the atmosphere (~15 km).

Thank you for attention!

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